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Implications of Developing Deep-Sea Arctic Fisheries for Greenland Halibut (Reinhardtius hippoglossoides): Inshore Stock Connectivity and Capture Induced Stress of Ecologically Important Fish Species

Amanda Noel Barkley
University of Windsor

Implications of Developing Deep-Sea Arctic Fisheries for Greenland Halibut (*Reinhardtius hippoglossoides*): Inshore Stock Connectivity and Capture Induced Stress of Ecologically Important Fish Species

By

Amanda Barkley

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Implications of Developing Deep-Sea Arctic Fisheries for Greenland Halibut (*Reinhardtius hippoglossoides*): Inshore Stock Connectivity and Capture Induced Stress of Ecologically Important Fish Species

by

Amanda Barkley

APPROVED BY:

_____

Dr. Oliver Love
Department of Biological Science

_____

Dr. Daniel Heath
Great Lakes Institute for Environmental Research

_____

Dr. Nigel Hussey, Co-Supervisor
Great Lakes Institute for Environmental Research

_____

Dr. Aaron Fisk, Advisor
Great Lakes Institute for Environmental Research

26 August 2015

DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is a result of a joint research, which was undertaken under supervision of Drs. Aaron Fisk and Nigel Hussey. The collaboration is covered in Chapter 3 of the thesis. This manuscript was coauthored by A. Barkley, S.J. Cooke, A.T. Fisk, K. Hedges, N.E. Hussey. Throughout the thesis, main ideas, data analysis and interpretation were performed by the author, and the contribution of co-authors was through theoretical knowledge input, help with statistical analysis of the data and guidance through the writing process, including revisions of the drafts.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis.

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II. Declaration of Previous Publication

This thesis includes 1 original paper that has been previously submitted for publication in peer reviewed journals, as follows:

Chapter 3: Capture-Induced Stress in Deep-Water Arctic Fish Species (*Manuscript submitted to Polar Biology: submitted July 2015*)

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ABSTRACT

One of the most pressing issues facing developing Arctic fisheries is a lack of scientific knowledge available to inform management. This thesis develops two key ideas essential to establishing a sustainable harvest of Greenland Halibut (*Reinhardtius hippoglossoides*) within Scott Inlet, Baffin Island: inshore/offshore connectivity of Greenland Halibut stocks, and capture induced stress of Greenland Halibut and Greenland Shark (*Somniosus microcephalus*). The majority of Greenland Halibut only utilised the inshore environment during the summer, ice-free, season spending about 27±14 days within the system before exiting offshore. A small resident portion of fish, spent on average 261±79 days within Scott Inlet throughout the year. Capture stress indicated that undersized Greenland Halibut do not express greater physiological perturbations, yet Greenland Sharks captured at greater depths had higher lactate values (300-600 m: 1.6±0.5 mmol/L and 700-900 m: 3.7±1.2 mmol/L). This information will contribute to the sustainable development of Greenland Halibut fisheries in the Arctic.

DEDICATION

I would like to dedicate this thesis to my parents, Nancy and Paul Barkley, for all their love and support, and for inspiring my love of science by teaching me that it's fun to play in ditches and creeks, catching frogs and minnows.

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CHAPTER 1

General Introduction

1.1 Arctic Fisheries

Multiple methods exist to characterize the boundaries of the Arctic, from simply defining the latitude of the Arctic Circle at 66° 33'N, to providing a more biologically relevant extent that includes all northern localities within the 10°C summer isotherm. Much of the land is covered in permafrost where no trees can grow, only small shrubs and grasses. The marine environment is characterized by yearly ice cover that, depending on latitude, persists throughout most of the year. The human population within the Arctic consists of just over 4 million people, of which a high percentage are indigenous (Helemiak and Bogoyavlensky 2015). The indigenous cultures of the Arctic are highly specialized for survival in the cold and harsh environment, and much of that stems from knowledge and reliance on the marine environment (Schweitzer et al. 2015).

The traditional use of marine resources in the Arctic centered on subsistence hunting, a non-monetary economy that relies on hunting and trapping for nutrition and survival (Schweitzer et al. 2015). The primary resources targeted within the Arctic were marine mammals such as seal (mostly ring seal, *Phoca hispida*), whales (narwhale *Monodon monoceros*, and bowhead whales *Balaena mysticetus*) and fish (such as Arctic Char *Salvelinus alpinus*). The products obtained from these resources (food, oils, skins) would then be used by the family, or shared between individuals within the region (Reist et al. 1997). Even with the introduction of western civilization and traditions, the subsistence economy within the Arctic has remained a central part of northern culture, where traditional marine resources provide essential nutrients that are lacking, or are simply too expensive to purchase in Northern co-ops (Reist et al. 1997, Schweitzer et al. 2015). Arctic fisheries are typically classified as mixed economies; due to the combination of both subsistence and commercial harvesting that supply both resources and wealth to the region.

Much of northern Canada is within the Arctic Circle and home to a diverse culture of Inuit aboriginal people. This land is referred to as Inuit Nanangat, which consists of the land, water and ice surrounding the traditional Inuit homeland. However, with the introduction of western culture, many of these communities continue to be afflicted by the transgenerational effects of colonization, such as rapid social and cultural change combined with limited career opportunities (Evans-Campbell et al 2012, Wexler 2014). This cultural loss has led to poor socioeconomic conditions in many Inuit communities throughout the north (Simon 2011). The development of sustainable commercial fishing industries has the potential to provide much needed economic input to arctic communities while maintaining cultural traditions by incorporating historical knowledge of the land and sea. In an effort to promote the development of small-scale artisanal fisheries that are driven by the interests and concerns of Inuit communities, the 12 nautical miles offshore of Nunavut were designated to exclusive management by the Nunavut Wildlife Management Board (NWMB) through the Nunavut Land Claims Agreement (Government of Canada; NLCA 1993) known as the Nunavut Settlement Area (NSA). The designation of local management encourages social cohesion within communities as fishermen work together to promote the values most important to them (Pomeroy 1995). The rest of the offshore marine environment within the Eastern Canadian Arctic (NAFO subdivisions 0A and 0B) is managed by the Department of Fisheries and Oceans (DFO) Canada where it does not cross the exclusive economic zone (EEZ) of other countries (i.e. Greenland) (DFO 2013).

The two primary fish that are targeted for commercial harvest in the inshore NSA are Greenland Halibut (*Reinhardtius hippoglossoides*) and Arctic Char. Combined, the commercial harvest is thought to contribute around 12 to 14 million dollars to the territory of Nunavut, and include about 300 seasonal jobs (Anonymous 2005). The majority of the fish yield comes from Cambridge Bay which targets Arctic Char, and the community of Pangnirtung which harvest both Arctic Char and Greenland Halibut within Cumberland Sound (Anonymous 2005). The offshore

environment is typically harvested by vessels of southern Canadian origin targeting both Greenland Halibut and Northern Shrimp *Pandalus borealis* (Richards 2014). The lack of Inuit offshore vessels is the result of limited infrastructure within northern communities, as many do not have harbor or port facilities.

Inuit hunters have traditionally harvested fish such as Arctic Char for many years, yet the commercial fishing industry within the Canadian Arctic is still in its naissance. As a rich and relatively untouched environment, the Arctic is increasingly drawing interest from developers looking to exploit its natural resources (Christiansen et al. 2014). Global climate change is also expected to be most noticeable within polar regions, as summer temperatures increase, ultimately reducing the sea ice extent and providing more opportunities for offshore vessels to access marine resources (Karl & Trenberth 2003, Christiansen et al. 2014). One of the greatest challenges facing this industry moving forward is the lack of scientific research on important commercial species as the harsh environment and limited land-based resources have hindered potential advancement (DFO 2013). Total allowable catch (TAC) estimates can be overestimated when faced with inadequate or insufficient data on harvested species, quickly leading to overexploitation of the fish stock (Balton 1996). Concurrent with the movement towards ecosystem-based management, it is also important to consider the impacts that developing fisheries will have on both targeted species as well as by catch and ecosystem functions. The developing Arctic fishery is in a unique position to utilize the knowledge gained from past mistakes with southern fish stocks to develop a sustainable management plan that can take into account future environmental variability and maintain the ecosystem integrity for future generations.

1.2 Fish Movements & Acoustic Telemetry

One of the most important issues in fisheries management is stock identification. Through knowledge on stock structure, management boundaries can be established in such a way that each stock has a sustainable quota that allows only a certain amount of fish to be removed

each year (Waldman 2005). Yet problems arise due to the fact that management boundaries are rarely designed based on species biology, but instead are driven by economic and political borders. Commercial species that are highly migratory tend to cross multiple management boundaries, becoming straddling fish stocks that need special consideration to coordinate management between different zones (Meltzer 1994). Identifying straddling stocks and the influences that drive species migrations allows the establishment of sustainable fisheries practices that take into account future changes in habitat needs.

Fish may perform long distance or small-scale movements and migrations for a number of reasons. This includes changes in seasonal environmental conditions, locating foraging areas with high prey abundance, as well as traveling to or from spawning or nursery grounds (Leggett 1977). Yearly migrations to spawning areas can result in large aggregations of valuable fish that are easy to harvest, yet the practice of targeting spawning fish can also be highly destructive to the overall population. This is particularly true with deep-sea species that are difficult to capture other than when they cluster on seamounts to spawn, providing an easy target for commercial vessels, but also critically reducing the spawning population of sensitive deep-water stocks (Norse et al. 2012). As the importance of certain habitats can also change with the age of a fish, it is critical to examine habitat use of juveniles, not just those of a commercially viable size (Nagelkerken et al. 2000). Fish often display ontogenetic shifts with age, changing diet and habitat preferences (i.e., switching from inshore to offshore habitats, from fresh to salt water or moving to greater depths) that influence the species distribution. Nursery grounds in particular are areas characterized by a habitat conducive to growth and reduced predation where juvenile fish are found in large abundance (Beck et al. 2001). As the fish age, they will migrate away from the nursery ground to exploit other resources. Identification of both nursery and spawning areas as large aggregations of small or spawning fish allows for fishing closures to areas important for species preservation (Beck et al. 2001, Sala et al. 2002). At the same time, it is critical to identify

the connectivity of harvested populations to these important life history grounds to determine the species distribution as well as the stock and population structure (Waldmen 2005).

Habitat selection and migration can be heavily influenced by environmental cues such as temperature, salinity, and ice conditions. Many fish species move to maintain optimal temperature regimes, be it daily for potential digestion benefits (Wurtsbaugh & Neverman 1988), or seasonal to maintain a suitable habitat during yearly temperature fluctuations (Leggett 1977). However, the environmental alterations brought about by climate change have the potential to drastically affect temperature, currents and ice cover of the world's oceans (Karl 2003). These changes will undoubtedly influence fish abundances and distributions as key habitats become inhospitable to the populations they once sustained (Baudron et al. 2014, Christiansen et al. 2014). Linking environmental stimuli with migration patterns in important commercial fish stocks provides the ability to predict how abundance and distribution will change in a changing environment, providing information on future sustainability.

Establishing a reliable estimate of migration patterns, especially in trans-oceanic fish species, has been no simple task. Many fisheries rely simply on capture information from commercial vessels or through scientific trawls that determine areas abundant with juveniles (potential nursery) or mature, spawning fish (potential spawning ground). However, this fails to determine the migrational patterns of fish travelling to and from these areas. Tag and recapture studies have elucidated a certain amount of population connectivity through dual point tracking of release and recapture location, yet captures are heavily influenced by fishing effort and it lacks fine-scale, repeated movements by an individual.

The development of passive acoustic tracking technology has facilitated the process of obtaining precise data on small and large scale fish movements, as the equipment can be left unattended for long periods of time. This method involves the surgical implantation of an

acoustic transmitter (abbreviated to tag) with a unique I.D. code into the study fish. The tag releases a pulse of sound at 69 kHz within a random time interval. This sound (or ping) is then detected by receivers that are moored underwater when the animal comes within range, and the unique I.D of the tag is recorded as well as the exact date and time of the detection. Thus, this system provides accurate information on the time at which an individual fish was in the given location of the receiver. This is known as passive tracking as it is not required that the researcher actively follow the animal they wish to study, but instead may set up arrays of receivers that will last over a year as they record long term data on the movements of aquatic species (Heupel et al. 2006).

1.3 Stress Associated with Commercial Capture of Fish

An animal's stress response is an adaptive mechanism that helps species cope with changes in the environment as well as avoid or escape detrimental situations (Barton 2002). The response is typically characterized by a change in the internal homoeostasis of an organism in response to a potentially harmful stimulus (Wendelaar-Bonga 1997). In aquatic ecosystems, many fish species face stressors that can be natural or anthropogenic in origin. Natural variability in the environment can lead to temperatures, salinity levels, and dissolved oxygen concentrations that require fish to either respond behaviorally or physiologically to compensate for the unfavorable conditions (Barton 2002). Most fish have adapted to respond to natural stressors, yet those imposed by humans, such as pollutants and commercial capture, can be more severe or last longer than natural occurrences. Many fisheries impose limits on the amount as well as size of fish that can be harvested, and all those outside of these criteria are released as discards, including non-target species. In the case of fisheries capture, the physiological stress response combined with the physical damage sustained through hooking or compression in a trawl net can result in reduced fitness of discards post-release (Kieffer 2000, Barton 2002, Pankhurst 2011). As bycatch often consists of ecologically important species, such as top predators that are key to trophic

stability, determining factors that increase capture related stressors can inform management to better practices that minimize the impact on fishery discards.

The physiological response of a fish to an acute stressful stimuli has been grouped into two major stages: the primary response, which is the release of corticosteroids and catecholamines, and the secondary response, characterized by metabolic changes and disruption in osmoregulation to list only a few (Wendelaar-Bonga 1997, Barton 2002). There is also a tertiary response that can be described as a change to the whole fish, as growth, swimming ability, and behavioral patterns are altered due to sever acute stress, or prolonged chronic stress (Wendelaar-Bonga 1997, Barton 2002). The numerous changes to the internal physiology of a stressed fish provide many different indicators of stress level that can be used to assess the effects of fisheries capture. Some of the most commonly used measures are cortisol, lactate, pH, glucose, and the partial pressures of oxygen and carbon dioxide, all of which are a part of the secondary stress response, except for cortisol (for example: Waring et al. 1992, Meka & McCormick 2005, Roth & Rotabakk 2012). Blood glucose and lactate in particular are good indicators of stress that can be immediately tested in the field without having to return samples to a lab, reducing handling time and making them ideal for research in harsh and logistically complicated environments. Hyperglycemia is commonly observed in stressed fish as catecholamines (particularly epinephrine) mediate the release of glucose stores in the liver and muscles so that it is readily available for cellular metabolism (Weedelaar Bonga 1997). Lactate on the other hand is the by-product of anaerobic cellular respiration and it accumulates in the muscles and blood as a fish struggles to escape capture (Gleeson 1996). This makes lactate an ideal indicator of physical exhaustion, and has previously been reported as a potential indicator of immediate and post release mortality caused by capture (Moyes et al. 2006, Marshall et al. 2012).

1.4 Greenland Halibut

Greenland Halibut (*Reinhardtius hippoglossoides)* are a deepwater flatfish with a circumpolar distribution throughout the northern Atlantic and Pacific oceans as well as up into the Arctic. As a member of the Pleuronectidae family, their body is laterally compressed; with dorsal and anal fins that extend along its length. They are right-eye flounders meaning that during metamorphosis from the larval stage, the left eye migrates to the right size of the body (Munroe 2005). However, the left eye of Greenland Halibut is located on the dorsal ridge, which potentially provides a greater range of view, and suggests that they may spend more time in the pelagic zone compared to other flatfishes (De Groot 1970). The location of the eye also suggests that they can swim vertically (similar to roundfish), yet evidence for escape behaviour in front of a bottom trawl demonstrated primarily horizontal swimming (De Groot 1970, Albert et al. 2003). Most flatfish lack melanin pigmentation on the blind side of their body, causing it to be a pale, white colour, yet Greenland Halibut display ambicolouration where both the blind and ocular sides of the body are pigmented a dark black, brown or grey, with the blind side only slightly lighter than the ocular side (Burton 1988). A relatively large fish, Greenland Halibut can reach a length of 120 cm, with females typically growing larger than males, yet most commercial catches have a mean size around 50 cm (Jørgensen 1997a). Greenland Halibut are also a slow growing species with maximum age estimates around 30 years (Treble et al. 2008).

Habitat preference of Greenland Halibut generally consist of temperatures around 1.3-2.7°C, where the bottom substrate is composed of mostly mud and/or sand (McConnaughey & Smith 2000, Peklova et al. 2012). As a deep-water fish species, they can be found at depths from around 200-1500 m, yet fish have been caught as deep as 2200 m (Boje and Hareide 1993, Peklova et al. 2012). Greenland Halibut progressively migrate to deeper water with age, as juvenile fish are found in the shallowest end of their depth range (around 200 m) whereas larger, mature fish are more typically found between 800-1000 m (Jørgensen 1997a, Peklova et al.

2012). The pelagic occurrence of Greenland Halibut is also most often seen in smaller fish (<20 cm) that migrate into the water column at night to forage (Jørgensen 1997b), yet based on stomach content studies, medium sized fish (20-50 cm) may also exploit the pelagic environment when prey such as Caplin (*Mallotus villosus*) are present (Bowering & Lilly 1992).

In the Northwest Atlantic it is believed that almost all of the Greenland Halibut stock originate from spawning grounds that extend from the Davis Strait, south to the Flemish Pass (Junquera & Zamarro 1994). Spawning takes place in the winter to early spring, and the eggs and larvae drift with the oceanic currents to rest on the slopes off Greenland and Canada (Rideout et al. 1999, Gundersen et al. 2010). Greenland Halibut captured from the Gulf of St. Lawrence and held in captivity were determined to be group-synchronous, determinate, and total spawners (Dominguez-Petit et al. 2013). They produce relatively few, large eggs that have a 50% incubation time of about 44 days at 2°C (Dominguez-Petit et al. 2013). Females also display a significant relationship of length and weight with realized fecundity, as larger females produce more eggs, yet the diameter and weight of the eggs remain constant across all sizes (Dominguez-Petit et al. 2013).

There exists a significant amount of gene flow throughout the entire Northern Atlantic population of Greenland Halibut, as there is very little genetic differentiation between the Western and Eastern Atlantic fish (Vis et al. 1997, Roy et al. 2014). In contrast, meristic and morphometric characters as well as variation in parasites indicate separation of sub-adult and adult fish from the Gulf of St. Lawrence, the offshore Atlantic and within Greenland fjords that are likely driven by rearing environment (Riget et al. 1992, Arthur & Albert 1993, Boje et al. 1997). To further elucidate habitat connectivity, tag and recapture studies have characterised the possible migration patterns of Greenland halibut, showing high residency within the inshore environment of West Greenland fjords, consistent with physical indicators of adult habitat separation (Riget & Boje 1989, Boje 2001). However, a small number of long distance migrants

were also noted, mostly from fish tagged offshore, from Newfoundland to the Davis Strait (Bowering 1982) as well as from Baffin Bay to Denmark Strait, connecting the Northwest and Northeast Atlantic stocks (Boje 2001). As commercial fishing activities frequently take place both within the inshore and offshore environment of the Northwest Atlantic Ocean, a better understanding of the connectivity of these habitats, as well as the status of potential resident populations, is important for sustainable management of the stock (Bowering & Nedreaas 2000).

A traditional fishery for Greenland Halibut existed within Greenland in the 1800s, yet harvesting at a commercial level in the Northwest Atlantic did not truly begin until the 1960s when cod and other flatfish industries in the Atlantic began to collapse (Bowering & Nedreaas 2000). The northern most extent of the fishery reaches into NAFO subareas 0 (the western half or Canadian EEZ of Baffin Bay and Davis Strait) and 1 (eastern, Greenland EEZ of Baffin Bay and Davis Strait) whose TAC was set at 25,000 tons from the years 1979-1994. During that time, total catch rarely reached the established limit (Bowering & Nedreaas 2000). After 1994 catch in zones 0 and 1 increased, leading to stricter management that determined specific TACs for the divisions within these two zones, yet the overall TAC for this area has increased to 30,000 tons for the year 2014 (Jorgenson & Treble 2014). Special consideration is needed for the management of Greenland Halibut as they are at a higher risk of overexploitation due to the life history traits described above (long life span, slow growth, and low fecundity) that are typical of deep-water species (Koslow et al. 2000). These traits are also common in the deep-water fish that exploit similar habitats to Greenland Halibut that ultimately become bycatch in the developing fishery (Norse et al. 2012).

1.5 Greenland Shark

Information on Arctic deep-sea fish is relatively scarce, yet biological information on important commercial fish such as the Greenland Halibut has started to increase in the past few decades in order to inform management. Other ecologically important species have not yet

reached the level of knowledge now available for commercial fish, even though fisheries can have a damaging impact on the populations of these species through unintended encounters as bycatch. Many countries are therefore moving towards an ecosystem-based approach to fisheries management that entails the establishment of management goals and protocols that address the sustainability of ecosystem composition, structure and function (Christensen et al. 1996). To this effect, it is no longer sufficient to solely focus on managing the targeted fish stock to maintain profitable commercial harvests, as the integrity of the ecosystem that hosts that stock is considered equally important. The importance of ecosystem conservation stems from the understanding that ecosystem integrity and complexity provide greater resilience to severe environmental disturbances and the foundations for adaptation to long-term changes (Garcia & Cochrane 2005).

The Greenland Shark (*Somniosus microcephalus*) is a deep-water, sub-arctic species from the family Somniosidae, or sleeper shark. As a large species, the Greenland Shark can reach a total length of 600 cm yet are more typically encountered at a length of about 300-500 cm (Templemen 1963, Yano et al. 2007). They range in colour from a dark, almost black pigmentation to light mottled grey with a heavy-set body and relatively small fins (MacNeil et al. 2012). One of the most notable features of the Greenland Shark is the common presence of the parasite *Ommatokoita elongata* (present on 98.9% of sharks caught in East Greenland) that attaches to the cornea of the eye and renders this species effectively blind (Berland 1961, MacNeil et al. 2012).

Information on Greenland Sharks has been relatively lacking from the scientific literature, with knowledge gaps concerning age, reproduction, population structure and migrations (MacNeil et al. 2012). Yet significant advancements have been made recently, identifying deep-water fjords such as Scott Inlet on Baffin Island as a potential nursery ground due to the high abundance of juveniles (<200 cm TL) that are rarely caught elsewhere within the

Arctic (Hussey et al. 2014). The use of pop-up archival transmission tags has also contributed to knowledge on depth and temperature preferences of Greenland Sharks as well as potential migration patterns throughout the Arctic and Northwest Atlantic (Fisk et al. 2012, Campana et al. 2013). Feeding studies using both stomach content and stable isotopes have determined this species to be an apex predator within the Arctic, consuming both pelagic and benthic fish such as Greenland Halibut, Atlantic Cod (*Gadus morhua*) and Redfish (*Sebastes mentella*) as well as both harp and ringed seals (Fisk et al. 2002, McMeans et al. 2010).

Traditional fisheries existed for Greenland Sharks that eventually developed to commercial harvests that targeted this species for its liver oil (MacNeil et al. 2012). However, today the greatest threat to Greenland Sharks are as bycatch of the Greenland Halibut fishery. Between 2009 and 2010 a combined weight of 106 tons in Greenland Shark were captured within Greenland Halibut trawls and gillnets in NAFO division 0 (DFO 2013). Ideally, sharks can be released from fishing gear alive as discards, but as they often tangle fishing lines, fishermen will remove their tailfin to avoid cutting the leaderline of the fishing gear (Idrobo & Berkes 2012). As a potential apex predator in the Arctic, Greenland Sharks may play an important role in trophic stability. Loss of such a species through poor management of bycatch can result in the devastating ecological effects of tropic cascades (Myers et al. 2007).

1.6 Rational and Objectives

This thesis provides information vital to the development and sustainable management of Greenland Halibut fisheries in the Canadian Arctic by describing stock connectivity between the inshore and offshore environment as well as examining capture induced stress metabolites in both target (Greenland Halibut) and bycatch (Greenland Shark) species. Many Inuit communities within the Canadian Arctic have expressed interest in developing winter artisanal fisheries to provide much needed economic development to the region. The current study area is located within Scott Inlet and Sam Ford Fjord on the northern face of Baffin Island, a traditional hunting

ground for the Inuit of the nearby community of Clyde River. The infrastructure and employment potential of developing a Greenland Halibut fishery within the area is of great importance to many of the residents.

As a part of the Nunavut Land Claims Agreement, Scott Inlet and Sam Ford Fjord are both under the management of the NWMB and any commercial fishing that develops in the region must be based out of local communities. However, large commercial vessels are already harvesting Greenland Halibut in the offshore environment within NAFO division 0A. Little knowledge exists on the connectivity of the inshore and offshore environment for Greenland Halibut, especially along the Canadian coast. Tag and recapture studies on Western Greenland shores suggest there may exist resident populations within fjords, yet these studies are highly prone to bias, as fishing effort is much greater inshore than it is offshore (Boje 2001). With the use of acoustic telemetry, it is possible to track an individual fish as it moves throughout the study system on a yearly basis, providing high-resolution movement data on seasonal habitat use. Chapter 2 of this thesis aims to analyze the inshore/offshore connectivity of Greenland Halibut as well as smaller-scale migrations within the inshore environment. I hypothesize that there exists a resident population of Greenland Halibut within Scott Inlet and Sam Ford Fjord that remain within the system year-round. As the Arctic Ocean is characterized by two distinct seasons, ice-covered and ice-free, I also hypothesis that Greenland Halibut perform small-scale movements within the study system, residing primarily within the fjords during the ice-covered season, then moving into coastal regions in the summer to exploit the rich abundance of prey brought about by the short season of high productivity.

Fisheries discards are typically composed of undersized, juvenile target species and non-target accidental catch. The ability to release bycatch alive contributes to the maintenance of ecosystem integrity and reduces the overall impact of the fishery. Stress indicators provide a way to detect species life-stages that are particularly prone to detrimental fisheries interactions as well

as identify fisheries practices that may increase risk to discards. Very few studies to date have examined stress physiology in Arctic fish, which may provide insights into species resilience. Chapter 3 of this thesis therefore aims to assess capture related stress metabolites (lactate and glucose) of Greenland Halibut and Greenland Sharks for the first time to explore potential ontogenetic and capture related variations in stress. I hypothesize that smaller Greenland Halibut will express higher levels of blood glucose and lactate compared to larger fish as their active, pelagic lifestyle results in higher susceptibility to capture stress. Greenland Sharks will express higher levels of lactate and glucose as capture depth increases, and the additional effect of TL will also be explored.

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CHAPTER 2

Transient behaviour of the deep-water flatfish, Greenland halibut (*Reinhardtius hippoglossides*), in Arctic coastal fjords

2.1 Introduction

The impact small-scale fisheries can have on economic stability in under developed coastal communities has received increasing attention from governments and international organizations within the past decade (Kurien & Willmann, 2009). Providing revenue to local economies through the employment of fishermen and workers at fish processing plants, small-scale fisheries ultimately contribute more to poverty prevention and food security than their larger counter-parts (Allison & Ellis 2001, Béné 2003, Kurien & Willmann 2009). This has led to efforts to promote and manage small-scale fisheries in many countries (for example the Philippines and Uruguay) through providing local people preferential access to designated inshore areas close to their communities (Pomeroy 1995, Trimble & Berkes 2015). In certain cases, communities are also given control over management of the fishery to promote cohesion between local fishers, while working in cooperation with the federal government (Pomeroy 1995). However, the division of management areas between local communities and large commercial fishing vessels can lead to the over-exploitation of fish stocks when harvesting a common resource, a conflict that is intensified when harvesting targets the same group of migratory fish（Béné 2006).

In the Canadian Arctic, the Nunavut Wildlife Management Board (NWMB) has extensive decision-making jurisdiction 12 nautical miles offshore of the northernmost territory of Nunavut (NWMB Allocation Policy for Commercial Marine Fisheries 2012). This management boundary was developed as a part of the land claims agreement that provides indigenous Inuit communities preferential access to the natural resources of the Arctic (Nunavut Land Claims Agreement 1993).

Yet many Arctic communities continue to suffer from low income and a loss of cultural heritage resulting in socio-economic issues that could be alleviated by artisanal fisheries that adhere to traditional practices of hunting and trapping (Reist 1997). As traditional knowledge in the Arctic is heavily centered on marine resources, there exists a rich resource of information to draw from to aid the development of profitable and highly targeted small-scale fisheries in an ecologically sustainable fashion (Reist 1997, Idrobo & Berkes 2012).

Much of the exploratory fishing within the Canadian north has been focused on Greenland Halibut (*Reinhardtius hippoglossides*), a deep-water flatfish, found at depths from 200-1500 m and temperatures ranging from 4 to less than 0°C (Jorgenson 1997a, Peklova et al. 2012). Greenland Halibut are a highly valuable commercial species targeted by multiple countries throughout the Arctic and Northern Atlantic Oceans (Bowering & Nedreaas 2000). The Inuit community of Pangnirtung on Baffin Island, however, were the first to establish a local fishery targeting Greenland halibut in Canadian coastal waters through the use of longlines set through the ice during the winter months (Reist 1997). This Inuit coastal fishery, based on the highly successful Greenland model, has had very positive effects on the community with a set TAC of 500 tones since 2005 which can average about 1 million dollars in landings (DFO 2013). As a result, the development of coastal community fisheries in the Canadian Arctic is now viewed as a critical opportunity for Inuit to generate substantial revenues and contribute to local economies. However, with reduced sea ice extent and longer open-water periods, there is also growing interest to increase commercial fishing operations in the offshore environment as well as to develop a boat-based Inuit fishery (Christiansen et al. 2014). Continued expansion of fisheries could have serious consequences in the Arctic, as information on Greenland Halibut stock structure and habitat use remains largely unknown due to the harsh environment of the north that has traditionally limited scientific research (Reist 1997, Christiansen et al. 2014).

As a deep-water species, Greenland Halibut are thought to be susceptible to overexploitation, and notably the mean size of fish caught in the Northwestern fishery has declined since the 1980s (Koslow 2000). Greenland Halibut are a long-lived, slow growing species (Treble et al. 2008) with relatively large eggs and low fecundity (Dominguez-Petit et al. 2012). This suggests that, like many deep-sea fish, Greenland Halibut are particularly vulnerable to overexploitation and lack the resilience to re-establish healthy populations after substantial harvesting (Koslow 2000). The absence of clear population structure throughout the North Atlantic and Arctic Oceans also makes it difficult to define stock units, as Greenland Halibut are genetically homogenous (Vis et al. 1997, Roy et al. 2013) and can migrate extremely long distances (Boje 2001).

The development of both artisanal and large commercial fisheries in the Arctic requires better knowledge on how Greenland Halibut utilize inshore and offshore environments to define appropriate management boundaries and establish sustainable quotas. Current information suggests that the Greenland halibut populations in the northern fjords of Western Greenland are resident or 'sink' populations that do not contribute to the spawning biomass, while only a few migrant individuals exist in the southerly fjords (Boje 2001, Boje et al. 2014). Similarly, Greenland Halibut in Cumberland Sound on Baffin Island are considered to be a resident population which undertake a seasonal migration within the Sound (Treble 2003, Hussey, *unpublished data*). Given regional genetic homogeneity, however, questions remain over the level of connectivity that exists among these coastal populations and those further offshore in Baffin Bay and Davis Strait.

To successfully develop sustainable small scale fisheries for underdeveloped communities in the Arctic, knowledge on both small-scale movements to assist localized fishery efficiency and larger movements and connectivity to inform broader management is required. To this effect, the objective of this study was to determine the habitat use of Greenland Halibut in

Scott Inlet and Sam Ford Fjord, on Baffin Island, Canada, a potential coastal fishery location near the Inuit community of Clyde River. Specifically, through the use of acoustic telemetry within the deep-sea environment (200-1000 m), this study aimed to examine (i) small scale movements of Greenland halibut within these two coastal fjords and adjacent deep water channels, (ii) connectivity with the offshore environment of Baffin Bay (NAFO subarea 0A, Figure 2.1) to inform community development in the context of commercial offshore fisheries and (iii) the association of environmental cues with movements, as the Arctic is a changing environment where increased temperature and reduced ice extent can lead to future shifts in species distribution.

2.2 Methods

All fishing and telemetry mooring placements were performed aboard the Nunavut research vessel, R.V. Nuliajuk, in September 2012 and 2013 within and around Scott Inlet and Sam Ford Fjord on Baffin Island, Nunavut, Canada (approximately 71°15'N, 70°30'W). Acoustic monitor moorings consisted of a circular cast iron anchor and a two-meter rope riser to an EdgeTech Port MFE acoustic release. The release was then attached to a 14 m riser with an 18" or 16" float, depending on deployment depth. Vemco VR2W (69KHZ) acoustic monitors were attached to the top riser at approximately 10 m from the ocean floor with nylon zip ties, and the hydrophone pointing up. A total of 60 moorings were placed approximately 1 km apart in linear arrays, known as a gate or curtain, at seven locations throughout Scott Inlet and Sam Ford Fjord (Figure 2.2). These gates were set up to detect movements of Greenland Halibut to and from distinct habitats within the system, but most notably the outer line (labelled G7 on Figure 2.2) defines the boundary between Scott Inlet and Baffin Bay to detect fish that enter or exit the area. Gates such as G7 and G5 were established on the assumption that Greenland Halibut would travel only through the deep-water trenches of the study system, and so the total number of detections on each receiver was plotted based on receiver depth (binned into 100 m increases) to ensure that

fish were rarely detected on the shallow end receivers of these gates. Two moorings were lost during the study period, marked by open circles in Figure 2.2. As these were both located on interior gates, not the primary gate used within the analyses (G7), it was therefore determined that the loss of detectability of these two gates was considered acceptable.

In 2012, Greenland Halibut were caught using bottom longlines. Each longline consisted of a standard baseline rope (9.2 mm diameter tarred black sinking line) approximately 735 m long with 200 x 30 cm rope leader gangions with size 11 and 12 Tuna circle hooks spaced 30 cm apart. All hooks were baited with frozen squid. The longlines were set in the evening and retrieved the following morning. In 2013, Greenland halibut were caught using a Yankee style research bottom trawl (~1463 m of 1.43 cm diameter cable on each drum) at depths between 428 and 750. The trawl was fished in a straight line at a speed of ~3 knots (2.4-2.8 knots) for 30 min after settling to the bottom; the warp was adjusted to maintain an appropriate mouth opening for the depth fished (about 2 times water depth; mouth opening 40-60 m).

Only fish caught in good condition (minimal scale loss or capture related injuries and showing frequent gill movements) were selected for tagging. The acoustic tag was inserted into the body cavity through an incision made just below the pectoral fin on the ventral (non-ocular) side of the fish near the location of the liver. After being sterilized with diluted Betadine (5% povidone-iodine) the tag was inserted and the incision closed using 3/8 circle, 24 mm Vicryl sutures. Fish that were < 50 cm FL (fork length) were tagged using Vemco V13-1X acoustic tags (estimated tag battery life of 904 days), while fish > 50 cm FL were tagged using a V16-4X tag (estimated tag battery life of 3650 days). An external floy tag was inserted on the dorsal (ocular) side of the Greenland halibut, just below the dorsal fin. After surgery, tagged fish were held in black plastic containers with a continuous flow of fresh seawater to allow recovery (proper orientation in the water and frequent caudle fin and gill movements), and then released overboard near the location where they were caught. In total, 39 fish were tagged in 2012, and an additional

71 fish were tagged in 2013 resulting in 110 fish total with a mean size of 52±7 cm fork length (FL; range 40-76 cm). Release locations of these fish are marked on Figure 2.2.

Statistical Analysis

All detection data were filtered for false detections using the OTN SandBox application in R (R Core Development Team 2015), which uses the White-Mihoff False Filtering Tool. This involved filtering the entire detection dataset to determine any individual detections that were isolated by one hour (i.e., an individual fish was only detected once on one receiver in a gate over a time period of one hour). The application provides a file of all 'suspect' detections that were then manually examined. Manual examination found that none of the suspect detections were likely to be false detections based on the location of the detections preceding the suspect ones, so all data were included in the following analyses.

Only fish that were detected on a receiver at some point within the study time period (22 September 2013 to 31 August 2014) were considered for analysis. A limited array was established in 2012, as this was a poor ice year that limited the time available for field work, thus data from that year could not be included. However, as multiple fish tagged in 2012 were detected during the study time period, they were included in the analysis.

Small scale localized habitat use

The study area was separated into two major zones: the fjords, which consisted of Scott Inlet and Sam Ford Fjord as defined by Gates G3, G4, and G6, and the "middle basin" which is bounded by G7 (Figure 2.2). Most fish were tagged within the middle basin, therefore to be considered to have entered a fjord, they had to have two separate detection events on one of the entrance gates listed above, for the initial entry, then another when they left. The amount of time between those two detections was then assigned as the time spent within the fjord. A fish was assumed to have left the study area on the date of their last detection on G7, as long as they were

not detected again on any other receivers during the study period (22 September 2013 to 31 August 2014), or if they were detected again on G7 after a significant amount of time had passed (over 60 days) then they were assigned to have left then returned. Fish that were detected on the gates within the middle basin (G1, G2 and G5) yet never detected on G7 (or detected on G7, but then again on G7 within the 31 day period, or any other gate) were assumed to have remained within the middle basin year-round. Fish tagged in 2012 that were detected within the array were assessed based on the location of their first detection, that is, if their first detection was on G7, then they were assumed to be absent from the system until that first detection on G7 (same for fish tagged outside G7 in 2013). If their first detection was on an interior gate, then they were assumed to be present within the system from the start of the study period (however upon data inspection there were no fish that met this criteria). All this information was then combined to give the total number of days each fish spent within the fjords or middle basin over the study period (total of 344 days).

Differences in habitat use among individual fish within the system were examined using Ward's hierarchical cluster analysis with squared Euclidean distances. All data were transformed using z-scores to ensure equal influence of each parameter to cluster formation. This analysis was based on the following data, (i) the number of days each fish spent in Scott Inlet or Sam Ford fjord, (ii) the number of days resident in the middle basin at the entrance to the two fjords, (iii) the total distance traveled, (iv) average speed throughout the detection period and, (v) fork length. Total distance travelled was calculated using the distance from the tagging location of the fish to the gate where they were first detected, plus the distance between any other gates in which it traveled, in kilometers. Midpoints were identified between gates where direct linear distances bisected land to make the measures more realistic. The value used for distance travelled is not the absolute, true value for that fish, but instead acts as a measure of mobility within the system, as fish that travel into the fjords, or that frequently move back and forth between different gates will

have a higher value than those that are detected only on one or two gates. Average speed (in meters/second) was then calculated as the distance between each gate divided by the time it took to travel between those gates, and the overall average taken for all measures, as this will separate out fish that make fast, direct movements from those that move between gates at a slower pace. Following hierarchical cluster analysis, values for each parameter described above were plotted by identified cluster group.

Environmental cues for movement

Each fish was considered as either present or absent from the inshore environment on a daily basis over the study period based on the criteria described above. That is, if the fish was present in the middle basin or within the fjords it was assigned a '1', i.e. present in the inshore environment, but if it was detected on G7 and then not subsequently detected on any of the inner gates, or again on G7 within the next 60 days, it was assumed absent and assigned a '0', i.e. offshore.

Ice cover data was obtained through the Canadian Ice Service Archive (http://www.ec.gc.ca/glaces-ice/?lang=En&n=0A70E5EB-1) as weekly GIS ice cover charts for the Eastern Arctic from 1 September 2013 to 30 August 2014. These files were clipped to approximately 10 km north of Scott Inlet, 20 km south of Sam Ford Fjord and 65 km offshore of the study area. Ice concentrations within this region were then calculated by taking the total ice concentration of each polygon (as described by unique egg codes within the attribute table), multiplying the concentration by the polygon area divided by the total area of the study system, then adding the resulting values. All GIS computing was performed using ArcGIS 10.2 (Esri 2013).

To examine the factors driving the presence/absence of Greenland halibut within the study system, a general linear mixed effects model from the package MASS in R version 3.4.1

was employed (R Core Development Team 2015). Both fish identity and month were included as factors within the model, and then assigned as crossed random effects. Fixed variables included weekly ice cover (as described above), year tagged (as defined by dummy variables, 1 (2012) or 2 (2013)), and fish fork length. A temporal measure was not included as a fixed effect in the model due to its inherently high correlation with ice cover. Model selection was performed using the Wald statistic, removing consecutive individual fixed effects that were not significant at the α=0.05 threshold.

2.3 Results

In total, 65 fish were detected within the system from 22 September 2013 to 31 August 2014. This includes the detection of 57 fish tagged in 2013 (80.3% of the total) and an additional 8 fish tagged in 2012 (20.5% of the total tagged in that first year). Receivers placed in shallow water (<300 m) were the ones located at the ends of the gates on the upper slope of the trench. It is clear upon inspection that when Greenland Halibut cross a gate, they are being detected primarily within the deepest part of the channel (Figure 2.3), rarely using the upper shallow slopes. Therefore the assumption that monitoring only the deep-water areas of the study system should suffice to detect the majority of movements throughout the system was justified.

A total of 64 fish were included in the cluster analysis; one fish tagged in 2012 was excluded because it was only detected on G7, therefore distance and speed could not be calculated. The cluster analysis identified three groups of movement behaviours (Figure 2.4). Fish in Group 1 (n=34, 53% of the total) all left the study system between the end of September 2013 and the end of November 2013 and were therefore characterized by low residence within the middle basin (21±13 days) and within the fjords (0 days, Figure 2.5). This group of fish is also characterized by a low travel distance within the system (23.149±10.982 km; fish typically only travelled from their tagging location to G7) and a low average movement speed (0.04±0.03 m/s; the time from tagging to first detection on G7 ranged from a few days to a month). Group 2 fish

(n=17, 27% of the total) also showed low residence (middle basin: 33±14 days) but were highly mobile within the system, making multi-day, highly directional movements, into Scott Inlet and Sam Ford Fjord that resulted in larger travel distances (123.559±45.004 km) and average speeds (0.14±0.06 m/s, Figure 2.5). Three fish within Group 2, however, showed a relatively high residency within the study system, but spent the majority of the time (~ 200 days) within the fjords rather than the middle basin. Lastly, Group 3 fish (n=13, 20% of the total) were resident within the study system for a large portion of the year. This group is the most variable (Figures 2.4 and 2.5), with some fish spending time within the fjords (17±36 days) while others remained relatively sedentary in the middle basin (261±79 days). This resulted in high variation in total distance traveled (111.715±60.316 km) as well as average speed (0.09±0.10 m/s). Size of fish was not a principal factor driving the clusters, yet there is a general trend of larger fish in the 'resident' Group 3 compared to smaller fish in the 'transient' Groups 1 and 2 (Group 3: 55.5±8.1 cm, Group 1: 52.3±6.4 cm and Group 2: 49.2±5.0 cm, Figure 2.5).

The GLMM indicated that ice cover (GLMM, $p<0.001$) and tagging year (GLMM, $p=0.01$) were the two influential factors in predicting the presence/absence of Greenland Halibut within the study system (Table 2.1). The negative predicted value for ice indicated that as ice formed, the probability of Greenland Halibut being present within the study system decreased (Figure 2.6). The significant effect of tagging year was a result of a higher probability of detecting 2012 fish following ice formation (Figure 2.6). This was consistent with the cluster analysis as the 2012 fish were mostly Group 3 'residents' and were generally larger (Figure 2.4).

2.4 Discussion

Through the use of acoustic telemetry, this study clearly demonstrates that the Greenland Halibut present within Scott Inlet and Sam Ford Fjord during the ice-free season (typically August and September) use this area as a transitory zone, as most fish leave by the time ice starts to form at the end of November. That is, the majority of Greenland Halibut tagged during the ice-

free season in Scott Inlet only spend about one month within the area and their departure is highly significantly timed with the development of surface ice. The high levels of connectivity between the inshore and offshore environment documented in this study have yet to be described for this species, as past studies have all suggested that northern fjord populations of Greenland Halibut are highly resident (Boje 2001, Treble 2003, Boje et al 2014). Given that the inshore environment of Baffin Island is designated as a separate management zone for the development of small-scale Inuit fisheries, these findings have clear implications for the future management and sustainability of Greenland Halibut fisheries in the Arctic.

Much of the standard tag and recapture work that has been performed on Greenland Halibut within northern Greenland fjords (Upernavik, Uummannaq, Torsukkattack) suggest that the populations are resident, with only slight intermingling between inlets, and fish rarely travelling offshore (Boje 2001). Within these inshore areas, tag recapture data showed that Greenland Halibut performed small-scale seasonal migrations, congregating within the innermost areas of the fjords in the summer, open water period (Boje 2001). In contrast, Greenland halibut monitored in Disko Bay (mid-western Greenland) using archival data storage tags undertook inshore migrations into Ilulissat Ice fjord during the winter rather than the summer, but similarly there was no evidence that fish left the system (Boje et al. 2014). This pattern of moving inshore during the winter months was also observed in Cumberland Sound, within the Canadian Arctic (Peklova et al. 2012, Hussey, *unpublished data*), where fish are also thought to be resident (Treble 2003). Scott Inlet, however, is geographically different from both Disko Bay and Cumberland Sound. The Scott inlet system consists of two very narrow, deep fjords that connect directly to the offshore environment through a deep-water channel, whereas both Cumberland Sound and Disko Bay are both very large bays with numerous fjords and inlets. This may explain the greater connectivity of Scott Inlet with the offshore environment of Baffin Bay compared to these large systems.

The high significance of ice cover for predicting the presence of Greenland Halibut within Scott Inlet indicates that the transient behaviour of these fish is potentially influenced by the Arctic seasons. This significance is important given that ice cover is strongly correlated to the random effect of month, yet still remains highly significant. Greenland Halibut typically reside at depths greater than 300 m (Jorgenson 1997, also see Figure 2.3 with detection depth), in an environment that remains relatively stable year-round, irrespective of ice cover (Bedard et al. 2015). However, Greenland Halibut are also known to feed in the pelagic environment, consuming prey such as Capelin *Mallotus villosus* and Atlantic Herring *Clupea harengus* (Bowering and Lilly 1992, Hovde et al. 2002, Dennard et al. 2009). The fish captured in trawls throughout Scott Inlet during the month of September 2013 frequently had distended abdomens, indicative of recent intense feeding, which was confirmed to be comprised of mostly Arctic Cod *Arctogadus glacialis* (*personal observation*). It is possible that Greenland Halibut from the offshore population of Baffin Bay therefore use the inshore environment on the northern coast of Baffin Island to forage for prey species that become abundant inshore during the highly productive ice-free season, such as Arctic Cod (Kessel et al. 2015). Further work is required in this direction, considering the high significance of ice cover for Greenland Halibut presence, that can help determine if it is truly a food-based migration, or if there is some aspect of the Arctic seasons (such as temperature) that might influence the benthic habitat of this species, driving it to migrate in order to accommodate to such changes.

The strong association of Greenland Halibut movements with ice cover is concerning, as deep-water species are typically considered to be more resilient to surface variability brought about by climate change (Rose 2005, Morgan et al. 2013). The deep-sea environment in the Arctic is relatively constant in terms of temperature and salinity throughout the year, even as surface ice forms and melts (Bedard et al. 2015). However, if Greenland halibut movements correspond to factors linked with ice cover (such as pelagic prey abundance) then it is possible

that climate change could have a greater effect on Greenland Halibut abundance and distributions than previously thought (Rose 2005, Morgan et al. 2013). Reduced ice extent and concentration also limits the development of Inuit through-ice fisheries, as fishing is not possible if the ice is unsafe for travel. The socio-economic benefits that can be gained through the development of small-scale fisheries in the Arctic are therefore reduced, pointing to the twofold social and environmental impacts brought about by a warming Arctic environment (Ford 2009).

As is clear, most of the Greenland Halibut tagged in the current study do not reside within Scott Inlet for long. Yet the cluster analysis identified three unique behavioural types within the system. Groups 1 and 2 both exit Scott Inlet around the time of ice formation, but are separated through their variable use of the habitat while present as Group 2's tendency to make quick forages into the fjords increased both their speed and total distance traveled. The separation of fish in Group 3, who are the more 'resident' individuals, demonstrate that this inshore habitat may also host a smaller, local population typical of what was seen elsewhere in the Arctic (Boje 2001, Treble 2003, Boje et al 2014, Hussey, *unpublished data*). The presence of spatially overlapping resident and migratory fish has also been observed in Winter Flounder *Pseudopleuronectes americanus* (Sagarese & Frisk 2011), Plaice *Pleuronectes platessa* (Dunn and Pawson 2002), Atlantic Cod *Gadus morhua* (Cote et al. 2004) as well as many other species (reviewed in: Chapman et al. 2012). Numerous ecological drivers exist to influence variation in migration patterns, such as skipped breeding (where the resident fish lack sufficient energy stores to complete a spawning migration), variation in physiological tolerance (larger fish may be able to over-winter in habitats unsuitable for juveniles) or predation risk (smaller fish more mobile to avoid predation)(Chapman et al. 2012).

Drivers influencing variation in behavioural types of Greenland Halibut were not directly assessed in this study, yet the slight increase in body size of resident fish provides an interesting area for future study. Tagging studies typically target larger fish, as they are of most interest to

fisheries and management, are more likely to be recaptured, can better handle large tags and are more likely to survive when released (Bowering 1982, Peklova et al. 2012, Boje et al. 2014). The average size of Greenland halibut analyzed in Boje et al. (2014) was 59 cm (body length), while Peklova et al (2012) tagged fish > 80 cm FL. In the present study, fish were much smaller, with a mean ± SD of 52±7 cm FL. Greenland Halibut exhibit multiple changes in habitat use as they age, most notably migrating to deeper water, as those around 11 cm typically settle at 200 m depth, and progressively larger fish are caught as depths increasing to 1,000 m (Jørgensen 1997a). Smaller fish are also more likely to travel into the water column, as indicated by pelagic trawls (Jørgensen 1997b) and stomach content which shows a switch from pelagic prey to more benthic species with age (Rodriguez-Marin et al. 1995, Jørgensen 1997b, Hovde et al. 2002). It is therefore possible that the small fish tagged in this study exhibit a more transitory lifestyle that follows the abundance of pelagic prey throughout Baffin Bay, whereas larger fish are more sedentary within the inshore environment. The resident Greenland Halibut in Scott Inlet were of a marginally larger size, and may therefore represent fish on the cusp of this life style switch and the variation in size relates to variable growth rates and age among individuals (Treble 2008). However, size was not significant in the GLMM to predict the presence or absence of Greenland Halibut within Scott Inlet and size was used within the cluster analysis to group fish, therefore potentially influencing the distribution. Further tagging work targeting larger Greenland halibut within Scott Inlet will be required to address this point.

The use of acoustic telemetry to examine fish movements in the deep waters of the Arctic Ocean provides a novel approach to quantify behaviours of these little know species. However, this method has certain limitations, especially when used to study movement over a large region (Heupel et al. 2006). Assumptions must be made on the movement direction of fish and their presence or absence in the system, as it is possible that a fish detected on G7 did not continue out to Baffin Bay, but instead remained within the middle basin. Yet the fact that many fish move

throughout the system when present (especially given the high number of detections on G5) provides confidence that a final detection on G7 indicates a departure. It is unlikely that Greenland halibut remain motionless within the confines of G1, G2, G5 and G7 for an entire year given the mobile behaviour of the species (Peklova et al. 2012; Boje 2014; Hussey, *unpublished data*). The loss of moorings is a risk all telemetry studies must take, and in this case, there existed a gap in both Gates 2 and 4 that could allow Greenland Halibut to travel into Scott Inlet undetected. However, the chance that a fish goes undetected on both gates is exceptionally low. Only one fish successfully evaded G2 but was subsequently detected on G3 and G4. As the primary analysis of this study centered on G7 which detected when fish exited the study system, the gaps within the interior gates were considered acceptable within the overall study design.

As governments increasingly designate inshore areas to local communities to promote small-scale fisheries, a better understanding of the connectivity of this habitat with the offshore environment is needed if large-scale commercial vessels are harvesting the same species as those inshore (Allison et al. 2001). The current study highlights connectivity in Greenland Halibut populations that utilize the inshore environment during the ice-free period in the Arctic Ocean, an area designated for the development of artisanal Inuit fisheries, with the offshore. TACs assigned to fisheries that develop within Scott Inlet and Sam Ford Fjord during the ice-free season have to be subtracted from the offshore allotment as they are effectively harvesting the same fish. However, Inuit fisheries are typically ice-based, harvesting Greenland Halibut in the winter months using longlines while the offshore fishery is restricted to open water. A winter fishery would therefore be unlikely to target the transitory fish described in this study, and would instead be harvesting the resident individuals. Tagging fish captured in the winter would help to further elucidate the true presence of resident fish, as well as provide a larger sample size to determine their local habitat use.

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Table 2.1: Results of the generalized linear mixed effects model (GLMM) performed on Greenland Halibut presence/absence within Scott Inlet with only the significant variables of the final model.

Random Effects	**Standard error**			
Fish number	5.77			
Month	5.32			
Fixed effects	**Value estimate**	**Standard Error**	**t-value**	**p-value**
Intercept	5.84	2.18	2.68	0.0074
Ice	-7.69	0.69	-11.09	<0.001
Tag Year (2013)	-6.04	2.29	-2.64	0.0104

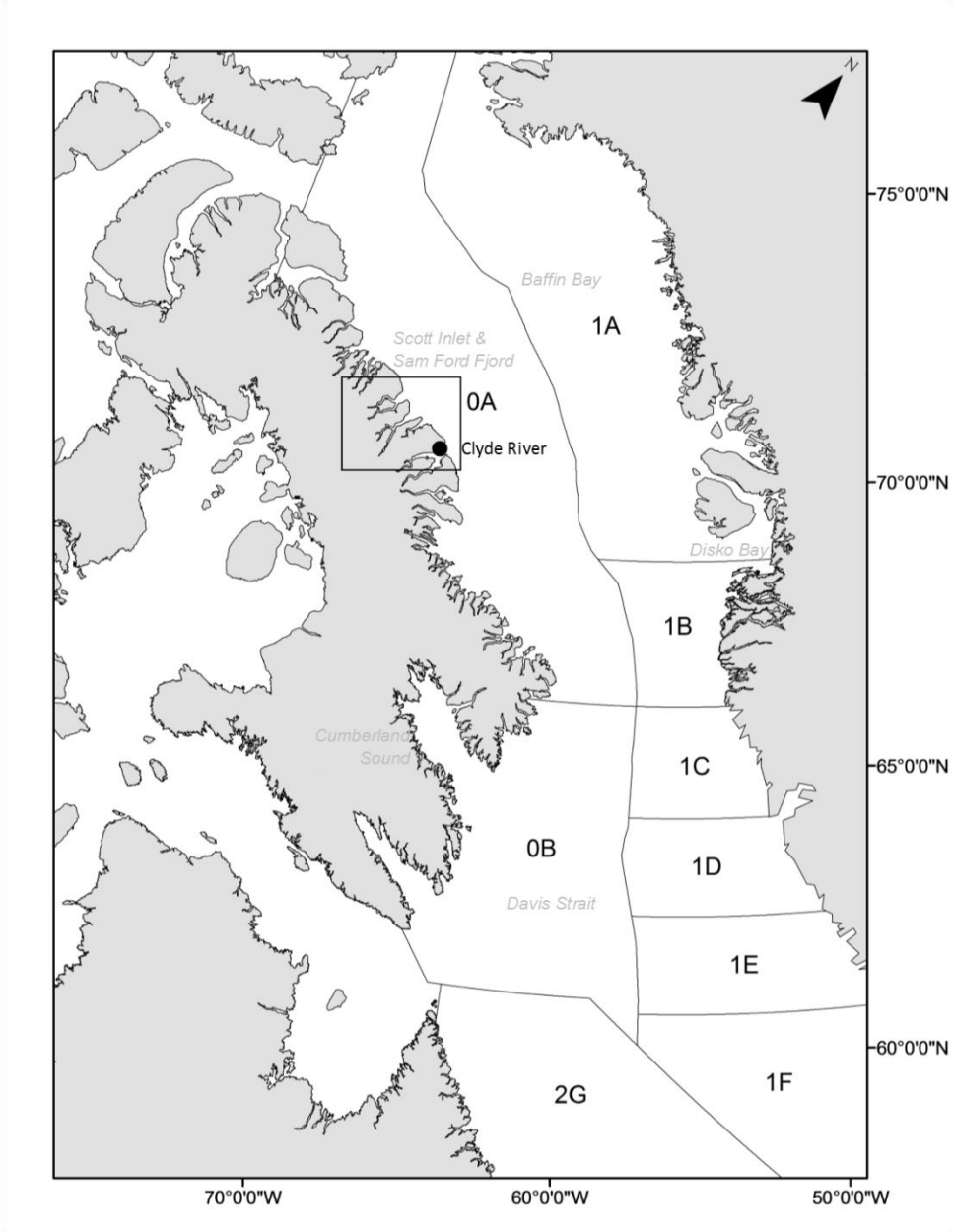

Figure 2.1: Map of Northwest Atlantic Fisheries Organization (NAFO) divisions within Baffin Bay and the Davis Strait. The square denotes the study area of Scott Inlet and Sam Ford Fjord, within the management boundary of 0A. The circle is the location of the community of Clyde River. NAFO divisions obtained from their website: http://www.nafo.int/data/frames/data.html

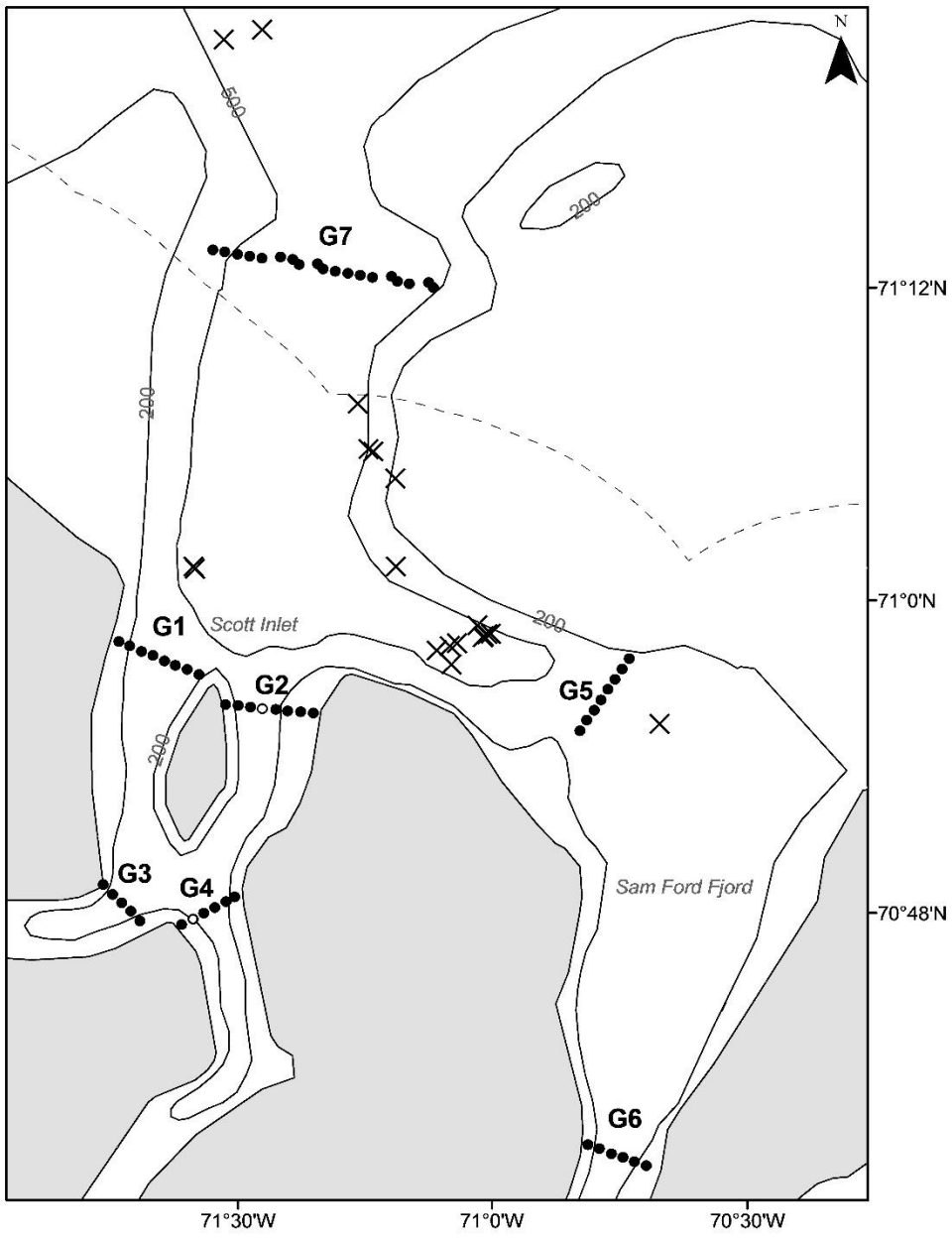

Figure 2.2: Map of Scott Inlet and Sam Ford Fjord, where Greenland Halibut were captured and tagged to determine their movements between the inshore and offshore environment. The dashed line represents the 12 nautical mile boundary of the NWMB. Each individual black dot represents an acoustic receiver, and the label above each row of receivers the name of that monitor curtain/gate. Open circles represent the two lost moorings. Release locations of the tagged fish are marked with Xs. Depth contours are marked for both 200 m and 500 m.

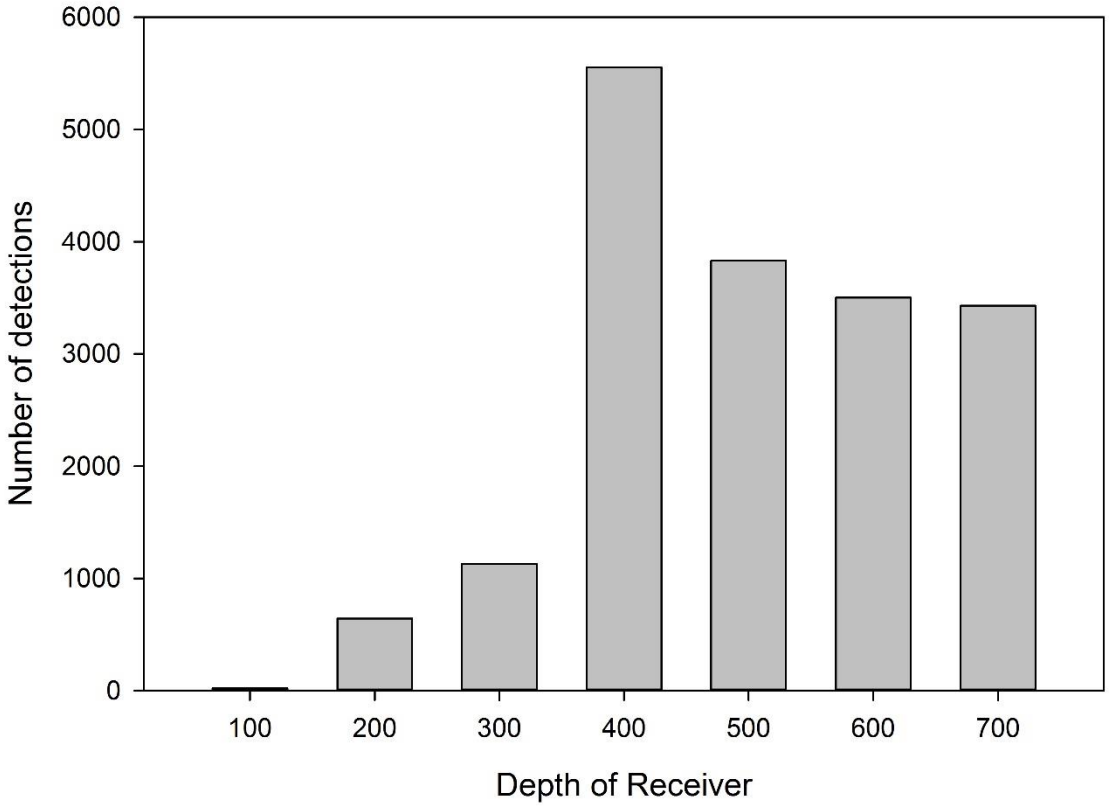

Figure 2.3: Total number of detections of Greenland Halibut that were acoustically tagged in Scott Inlet and Sam Ford Fjord, based on depth. Receiver depth was binned into 100 m groups, and the number of fish detections summed for each receiver depth.

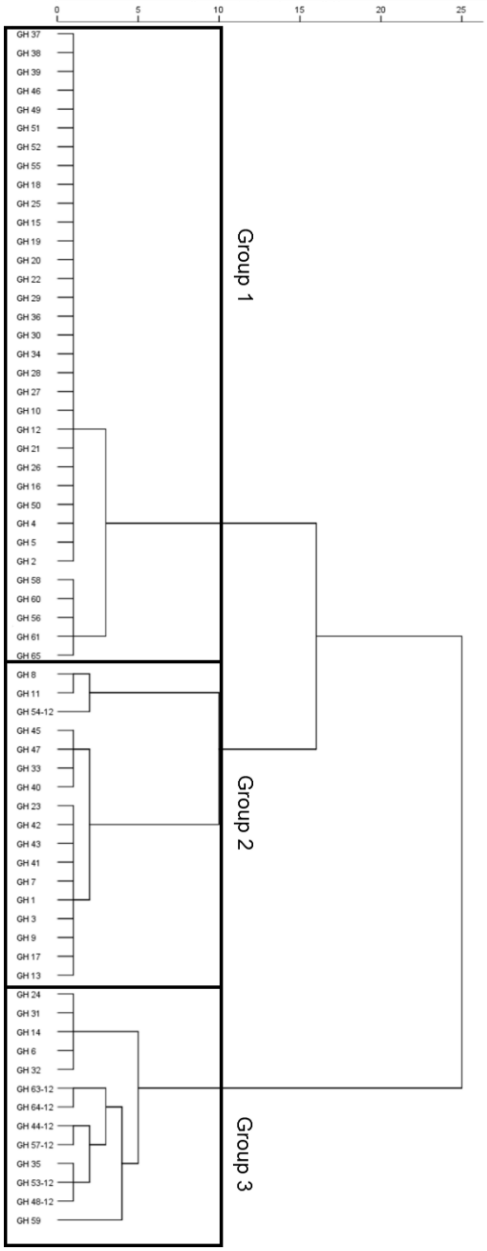

Figure 2.4: Dendogram of the hierarchal analysis with Ward linkage performed on acoustically tagged Greenland Halibut traits within Scott Inlet and Sam Ford Fjord. These traits were based on, days spent within the middle basin, days spent within fjords, total distance travelled, average speed and body size (fork length). The three selected clusters are highlighted with black boxes, and the group number indicated above the box. The fish with codes ending in '-12' are individuals tagged in September of 2012, the remainder were tagged in 2013.

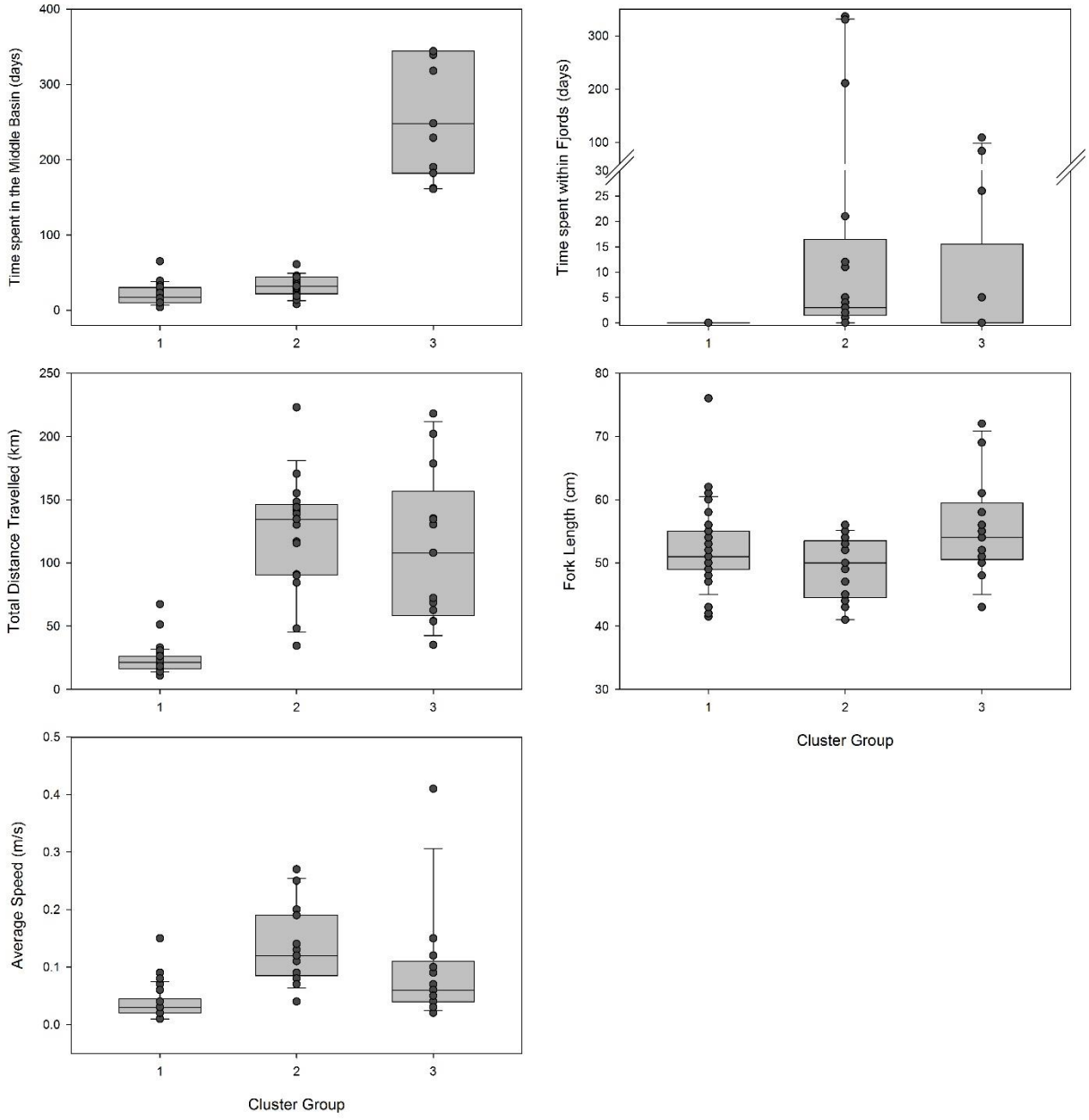

Figure 2.5: Traits of Greenland Halibut used for cluster analysis within Scott Inlet and Sam Ford Fjord. The groups identified in the hierarchal cluster analysis are plotted per criteria; (a) Days spent within the middle basin, (b) days spent within fjords, (c) total distance travelled (km), (d) body size (fork length - cm) and (e) average speed (m/s). The box represents the 25th to the 75th percentiles of the data, and the whiskers extend to the 10th and 90th percentiles. The line within the box represents the median value and the black dots are the raw plotted data. Note the line break in (b) for days spent within the fjords

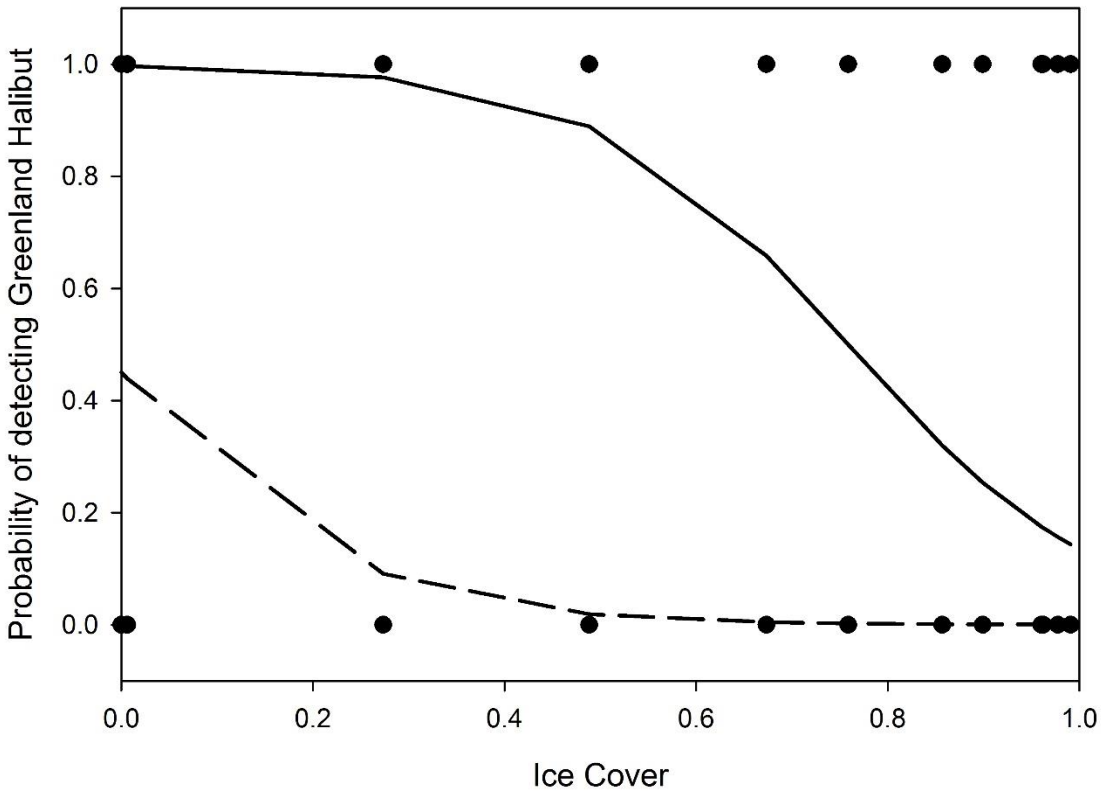

Figure 2.6: Probability of acoustically tagged Greenland Halibut being present within Scott Inlet and Sam Ford Fjord. Ice cover and the year Greenland Halibut were tagged were both significant predictors of Greenland Halibut presence based on the generalized mixed effects model (GLMM: ice, $p<0.001$; tag year, $p=0.01$). The solid line represents the probability of a fish tagged in 2012 being present within the system, and the dashed line is the probability of a fish tagged in 2013 being present based on ice cover. The dots are presence (1) or absence (0) of Greenland Halibut based on ice cover determined through acoustic telemetry.

CHAPTER 3

Capture induced stress in deep-water arctic fish

3.1 Introduction

Capture related stressors alter the internal homeostasis of fish and can potentially result in both lethal and sublethal physiological and behavioural impairments post release (Moyes et al. 2006; Donaldson et al. 2011; Rapp et al. 2012; Gallagher et al. 2014). These impairments are of concern for the sustainable operation of commercial fisheries where bycatch, including both non-target and undersized target species, are released to reduce the ecological impacts of the fishery (Hall et al. 2000; Davis 2002). The preservation of non-target species is important for maintaining ecosystem integrity, while the release of small individuals of the target species is thought to promote recruitment of the fished stock (Hall et al. 2000; Halliday and Pinhorn 2002). In general, we know little about the survival rate of discards due to the challenges of assessing post-release mortality in a realistic manner (Davis 2002; Donaldson et al. 2008). However, establishing measures of physiological disturbance for discards to assess the risk imposed by fisheries development (see Gallagher et al. 2014) can ultimately improve handling and harvesting practices to reduce the negative effects of capture to released bycatch and undersized fish.

The reduction of summer sea-ice and longer ice-free periods in the Arctic Ocean have led to increased interest in expanding commercial fisheries in the north (Christiansen et al. 2014). One of the primary targets is the deep-water Greenland Halibut (*Reinhardtius hippoglossides*), a circumpolar species inhabiting the benthopelagic zone of much of the Northern Atlantic, Pacific and Arctic Oceans (Bowering and Nedreaas 2000). This species exhibits many of the traits typical of deep-water fish that make them highly vulnerable to overexploitation, including long life span and slow growth (Treble et al. 2008). At present there are no size restrictions on catches of Greenland Halibut in Northern fisheries (DFO 2013), yet small, immature and unprofitable fish are frequently captured in trawls suggesting this approach may be sensible (Huse et al. 1999).

Concurrent with the growth of commercial fisheries for Greenland Halibut is concern over the adverse effects this fishery could have on Greenland Shark (*Somniosus microcephalus*) populations, as they are a frequently discarded bycatch species in the Arctic (MacNeil et al. 2012; DFO 2013). Greenland Sharks are an apex predator, and similar to Greenland Halibut exhibit slow growth, late maturation and likely low fecundity (Beck and Mansfield 1969; Yano et al. 2007; MacNeil et al. 2012). There have been targeted fisheries for Greenland Sharks in the past, however discard impairments and mortalities are currently the most prominent issue facing this species as Arctic fisheries develop (MacNeil et al. 2012; FAO 2014).

The primary objective of the current study was to assess the physiological response of both Greenland Halibut caught in a trawl and Greenland Sharks caught on bottom longlines through measuring blood lactate and glucose concentrations. Lactate and glucose are known to increase significantly in stressed fish, as glucose is released for energetic use, and lactate accumulates as a result of strenuous exercise in the absence of sufficient oxygen (Dobson and Hochachka 1987; Milligan 1996; Girard and Milligan 1992; Kieffer 2000). Secondary objectives include (i) assessing the effect of fish size on capture stress, as undersized Greenland Halibut may potentially become discards in a growing fishery and (ii) assess environmental factors (such as capture depth) for Greenland Shark stress levels, as this can prescribe areas that should be avoided by developing fisheries. Current knowledge on Arctic species is limited, and as exploitation continues to increase in the face of warming Arctic temperatures, a better understanding of physiological stress indicators in key commercial species is needed to help inform management to establish sustainable fishing practices.

3.2 Methods

All fish were captured aboard the Nunavut research vessel, R.V. Nuliajuk, in September 2013 and 2014 within and around Scott Inlet and Sam Ford Fjord on Baffin Island, Nunavut, Canada (approximately 71°15'N, 70°30'W). The surface water temperature was ~3°C, with

bottom temperatures remaining constant around 1°C at depths below 450 m as determined by CTD (conductivity, temperature, depth) casts performed on the vessel at the same time as fishing activities.

Greenland Halibut were caught in 2013 from a single bottom trawl at a depth of 700 m using a Yankee style research trawl (~1463 m of 1.43 cm diameter cable on each drum). The trawl was fished in a straight line at a speed of ~3 knots (2.4-2.8 knots) for 30 min after settling to the bottom; the warp was adjusted to maintain an appropriate mouth opening for the depth fished (~2 times water depth; mouth opening 40-60 m). When the net was brought to the surface, Greenland Halibut in good condition were immediately placed in a black plastic bin with a continuous flow of fresh seawater and held until testing. To obtain a blood sample, the caudle peduncle of each fish was severed and blood collected in a plastic vial. A drop of blood was then placed on the testing strip of a Lactate Pro LT-1710 portable analyzer (ARKRAY Inc., Kyoto, Japan), and an Accu-Chek® Compact Plus glucose meter (Roche Diagnostics, Basel, Switzerland), following standard protocols (Cooke et al. 2008; Stoot et al. 2014). The use of point-of-care devices to measure glucose and lactate have been validated through comparison to standard laboratory techniques in both teleosts and elasmobranchs. The Lactate Pro typically displayed a 1:1 ratio with laboratory values, with no significant variation in slop or intercept (Brown et al. 2008, Awruch et al. 2011, Serra-Llinares et al. 2012), however glucose values from Accu-Chek products are more variable, with a flatter slope that underestimates maximum values (Wells & Pankhurst 1999). However, point-of-care devices consistently show to be comparable within species sampled at the same time within the field and remain one of the best options when working in harsh and logistically complicated environments (Wells & Pankhurst 1999, Cooke et al. 2008, Awruch et al. 2011). The time from blood collection to analysis was <1 min. The time between testing each fish was ~6 min, leading to a sequential time range of testing from ~30 to 188 min following trawl capture.

Greenland Sharks were caught on longlines within Scott Inlet and Sam Ford Fjord in both 2013 and 2014. Longlines were soaked for an average of 12 hours at varying depths that were binned into three groups of 300-600 m, 600-700 m, or 700-900 m for data analysis. The bottom longline consisted of a standard baseline rope (9.2 mm diameter tarred black sinking line) approximately 735 m long with 50 x 1.5 m steel leader gangions with size 16 and 17 Tuna circle hooks spaced 5.5 m apart. All hooks were baited with frozen squid. Longlines were set in the evening and retrieved in the early morning. Hook timers were not available in this study; consequently, the length of time a shark was on the longline prior to hauling could not be determined. Once a shark was brought to the surface, two holding ropes were looped around the pectoral fins and the caudle fin, respectively. The shark was de-hooked from the longline and then held against a Zodiac for processing. Basic morphometric data (total length – cm), sex (presence of claspers to identify males) and blood withdrawal were then undertaken. Processing time of each shark was <20 minutes. To collect blood samples, the sharks were inverted to induce tonic immobility, and a small incision made with a scalpel blade between the pelvic and caudle fin. A 16-gauge needle attached to a 30 mL non-heparinized syringe was inserted into the incision, and approximately 10 mL of blood withdrawn. A drop of whole blood was immediately placed on to the glucose and lactate testing meters described above. In 2014, a Lactate Plus (Nova Biomedical®, Waltham, USA) analyzer was used to replace the Lactate Pro LT-17710, given both meters perform similarly (Tanner et al. 2010). The time from blood withdrawal to testing was <1 min.

All data were assessed for normality using the Wilks-Sharpiro test, and log-transformations applied where necessary. Multiple Greenland Halibut samples fell below the detection limit of the lactate analyzer (minimum detection = 0.8 mmol/L). As a result, the method of median semi-variance (SemiV) was used to apply values (with a range of 0 to 0.7) to the left-censored data as described in Zoffoli et al. (2013). The variance in the Greenland Halibut lactate

data could not be corrected by transformation, and therefore a generalized least squares model with an exponential variance structure was used instead of a traditional linear regression to model blood lactate concentration with both FL (fork length) and time since capture as well as their interaction. Greenland Halibut glucose values were modeled with a multiple linear regression using the same independent variables as lactate (FL and time since capture). A stepwise backward selection was used to determine the final model for both metabolites, removing insignificant terms based on the t-statistic. A linear regression was used to determine the relationship of Greenland shark lactate and glucose with TL (total length), then a t-test and one-way analysis of variance (ANOVA) was used to test the effect of sex and capture depth, respectively, on both stress metabolites. In the event the ANOVA was significant, a Tamhane post-hoc test was used to determine which depths varied significantly.

3.3 Results

Twenty-five Greenland Halibut ranging in size from 27-51 cm FL were sampled from the trawl. Eleven individuals had blood lactate levels below the detectable range of the analyzer; consequently, values used in the following analyses were assigned with the SemiV method (Zoffolie et al. 2013). This resulted in a range of lactate values from 0.2-2.8 mmol/L and mean (±SD) of 1.0±0.7 mmol/L. Time since capture was the only significant term in generalized least squares model ($t=2.83$, $p<0.01$, $\delta=0.78$, Table 1, Figure 3.1). Glucose values ranged from 1.1-3.7 mmol/L with a mean (±SD) of 1.8±0.6 and both time since capture ($t=2.11$, $p=0.05$, $\beta= 0.17$) and FL ($t=3.09$, $p<0.01$, $\beta= 0.03$) were significant ($F_{2,22}=5.20$, $p=0.01$, $R^2=0.32$, Table 3.1, Figure 3.1) in the regression model.

A total of 46 Greenland Sharks were captured on longlines with a size range of 150-341 cm TL. All sharks appeared in good condition and swam off vigorously upon release. There were no significant differences for either metabolite (independent samples T-test, $p>0.05$) between females (n=13) and males (n=14). Lactate ranged between 0.7-11.1 mmol/L and was significantly

different among depth stratum ($F_{2, 43}$=40.52, p<0.001, Figure 3.2) with sharks caught in shallower water (300-600m depth) having lower values (mean ± SD, 1.6±0.5, n=11) than those caught in deeper water (600-700m: 6.4±2.4 mmol/L (n=20) and 700-900m: 3.7±1.2 mmol/L (n=15), Tamhane post-hoc: p<0.05). Lactate did not have a significant relationship with TL. Glucose ranged from 2.6-8.1 with a mean (±SD) of 4.9±1.5 mmol/L and didn't vary significantly based on depth stratum (p>0.05) but the regression showed a significant effect of TL (F_{44}= 7.50, p<0.01, R^2= 0.15, Figure 3.2).

3.4 Discussion

The lactate values obtained for Greenland Halibut (1.0±0.7 mmol/L) were consistent with literature values of other flatfish species such as the Winter Flounder, *Pseudopleuronectes americanus* (1.3±0.7 mmol/L, Girard and Milligan 1992), Flathead Sole, *Hippoglossoides elassodon* (1.6±0.1 mmol/L, Turner and Wood 1983) and Pacific Halibut, *Hippoglossus stenolepis* (0.5±0.1 mmol/L, Davis and Schreck 2005). Flatfish and other sluggish or benthic species commonly express low lactate values compared to active pelagic species (Waring et al. 1992) as much of the lactate produced by muscular anaerobic cellular respiration remains within the muscles to be metabolized as opposed to being released into the blood (Wardle 1978; Girard and Milligan 1992; Dalla Via et al. 1997). The increasing linear relationship between lactate and time since capture for Greenland Halibut could be a result of flatfish typically requiring 2-3 hours post exercise to reach maximal values (Turner et al. 1983; Dalla Via et al. 1997, Barnette and Pankhurst 1998), and testing was completed after ~ 3 hours, which is insufficient time for values to drop. However, the increasing variability in the data, modeled by the generalized least squares method, from the initial to the final test suggests that some individuals may have begun to recover (Figure 3.1). Many factors can influence recovery rate, yet body size and temperature (as temperature was constant for all sampled fish), two principal parameters that affect recovery, were not influential in this study. Undefined parameters such as the variation in time of capture in

the trawl net, level of fasting, body condition among individuals, or intraspecific variability in stress response could influence this trend (Kieffer 2000).

The average lactate values obtained for Greenland Sharks captured on longlines (4.4±2.6 mmol/L) were comparable to species such as the Tiger Shark, *Galeocerdo cuvier* (4.9±6.0 mmol/L, Marshall et al. 2012) and Lemon Shark, *Negaprion brevirostris* (5.4±5.5 mmol/L, Hyatt et al. 2012), but more elevated than other species such as the Port Jackson Shark, *Heterodontus portusjacksoni* (1.3±03, Frick et al. 2010). The variability in lactate concentration of different species is likely driven by metabolic scope as it pertains to the species' ability to respond and recover from the homeostatic disruptions caused by capture (Skomal and Bernal 2010). The only significant predictor of lactate concentration for Greenland Sharks in the present study was capture depth, where sharks caught in the shallowest water displayed the lowest concentration (Figure 3.2). This could be caused by the longer time needed to bring the gear up from extreme depths and the dramatic changes in pressure that the shark experiences in the process, which also has the potential to increase mortality in certain species (Stewart 2008, Butcher et al. 2015).

Of the Greenland Sharks sampled in 2013, many had acoustic transmitters surgically inserted following blood sampling. Two of these sharks were not detected on a gate of monitors across the entrance of the fjord where tagging took place, possibly suggesting that they may have died after release (Hussey, *unpublished data*). Interestingly, one of these sharks had the highest recorded lactate concentration of 11.0 mmol/L, and the second was caught at the most extreme depth of 890 m (with a blood lactate concentration of 5.4 mmol/L, above the average for all the sharks sampled). Lactate has been cited as the best indicator of mortality in sharks, with moribund values ranging from 16±2 mmol/L in Blue Sharks, *Prionace glauca* (Hight et al. 2007) to 34.3±5.0 for Shortfin Mako, *Isurus oxyrinchus* (Marshall et al. 2012). Although data is limited in this study, future work combining stress indicators with post release telemetry tracking could

provide valuable information on the physiological indicators of short and long-term survival in this species (Donaldson et al. 2008).

Both Greenland Halibut and Greenland Sharks demonstrated an increase in blood glucose concentration with size (Figures 3.1 and 3.2). A possible explanation for this relationship is that glycogen stores are positively correlated with body size and therefore larger fish have the capacity to release greater amounts of glucose from the liver and white muscle tissues (Ferguson et al. 1993; Kieffer 2000, Skomal & Bernal 2010). The resultant physiological effects of this variation in stress response with respect to size is unclear, as smaller fish thus have a lower anaerobic capacity and may reach exhaustion faster than larger individuals, however they may also recover faster from minor stressors upon release (McDonald et al. 1998; Kieffer 2000; Gingerich and Suski 2012). Concurrently, the lack of a relationship between size and lactate concentration in both species may suggest that not all available glucose is used for anaerobic metabolism as a result of variation in individual activity levels and time of capture. Variation in capture related mortalities have been reported for different size classes of fish (Davis and Parker 2004; Morgan and Burgess 2007; Milliken 2009; Morgan and Carlson 2010), however the ability to predict survival based on physiological stress indicators remains uncertain, identifying that further research into physiology and post-release mortality is required (Cooke et al 2013).

There are a number of inherent challenges with studying the consequences of fisheries interactions on wild fish in polar regions. Obtaining baseline values is rather difficult given that most fish are captured at great depths, necessitating extra time to retrieve the fishing gear. Moreover, some species (e.g., Greenland Shark) are very large, which requires time to adequately restrain fish to enable phlebotomy. Future work could use hook timers on longlines to identify maximum set times for the gear that will minimize the Greenland Shark physiological stress response while maintaining targeted fish catch rates. Physiology requires context so information on reference ranges and how they vary relative to sex, maturation status, body size and season

will need to be considered. Perhaps the most exciting opportunities lie in coupling physiological sampling with survival analysis through the use of telemetry (see Donaldson et al. 2008). Such an approach will provide insights into the mechanistic basis for long-term survival and behaviour of these species and the risks associated with increased human activities and environmental change in the Arctic ecosystem.

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Table 1: Summary results for the significant statistical tests performed on Greenland Halibut and Greenland Shark stress metabolites (lactate and glucose) after capture in Scott Inlet, Baffin Island. Total sample size (n), range of fork length and total length (in cm) and the overall mean (±SD) of the given metabolite are listed on the left-hand side of the table. The statistical analyses with significant results are listed with all relevant parameters to the left.

Greenland Halibut (*Reinhardtius hippoglossoides*)

Stress Metabolite	n	Fork Length	Mean ± SD	Statistical Analysis	Variable	Parameter estimate	SE	t-value	p-value
Glucose	25	27-51	1.8±0.6	Linear regression R^2= 0.26 ($F_{2,22}$=5.20, p=0.01)	Intercept	-0.79	0.42	-1.89	0.072
					Time	0.17	0.08	2.11	0.05
					FL	0.03	0.01	3.09	0.005
Lactate	25	27-51	1.0±0.7	Generalized least squares	Intercept	0.42	0.12	3.02	0.006
					Time	0.37	0.13	2.83	0.01
					δ*	0.78			

Greenland Shark (*Somniosus microcephalus*)

Stress Metabolite	n	Total length	Mean ± SD	Statistical Analysis	Variable	Parameter estimate	SE	t-value	p-value
Glucose	46	150-341	4.9±1.5	Linear regression R^2= 0.13 ($F_{1,44}$=7.50, p=0.01)	Intercept	2.10	1.04	2.01	0.05
					TL	0.01	0.004	2.74	0.01
Lactate	46	150-341	4.4±2.6	ANOVA (by depth in meters)	Depth	Mean	SD	F-value	p-value
					300-600	1.6	0.5	40.52	0.001
					600-700	6.4	2.4		
					700-900	3.7	1.2		

* Delta (δ) is the estimated parameter for the power of the covariate variance structure used to model the Greenland halibut lactate data, as this data set did not meet the assumption of homogeneity of variance of simple linear regression after transformation

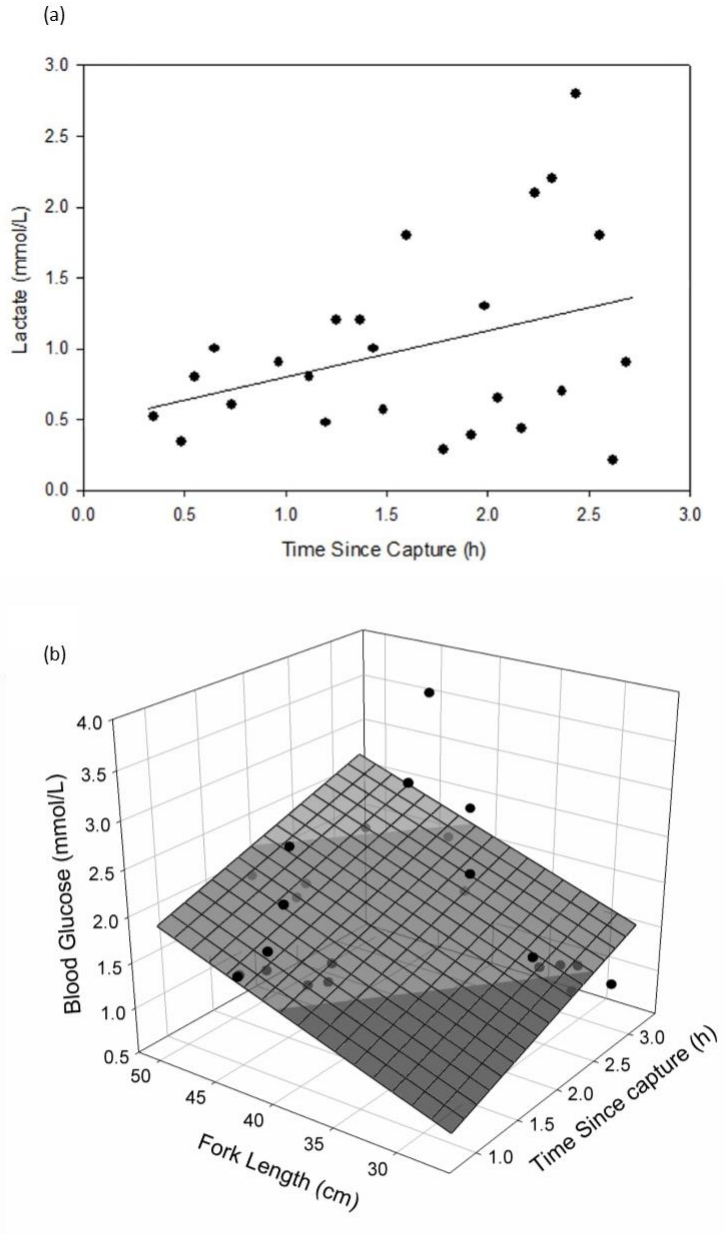

Figure 3.1 The relationship of Greenland halibut stress metabolites after capture in a bottom trawl in Scott Inlet, Baffin Island with the variables FL and time since capture as determined by backwards stepwise selection. (a) Generalized least squares model for Greenland Halibut lactate values where time since capture was the only significant variable ($t=2.83$, $p<0.01$, $\delta=0.78$). (b) Multiple linear regression for Greenland Halibut glucose with the significant variables time since capture ($t=2.11$, $p=0.05$, $\beta= 0.17$) and FL ($t=3.09$, $p<0.01$, $\beta= 0.03$, $F_{2,22}=5.20$, $p=0.01$, $R^2=0.32$)

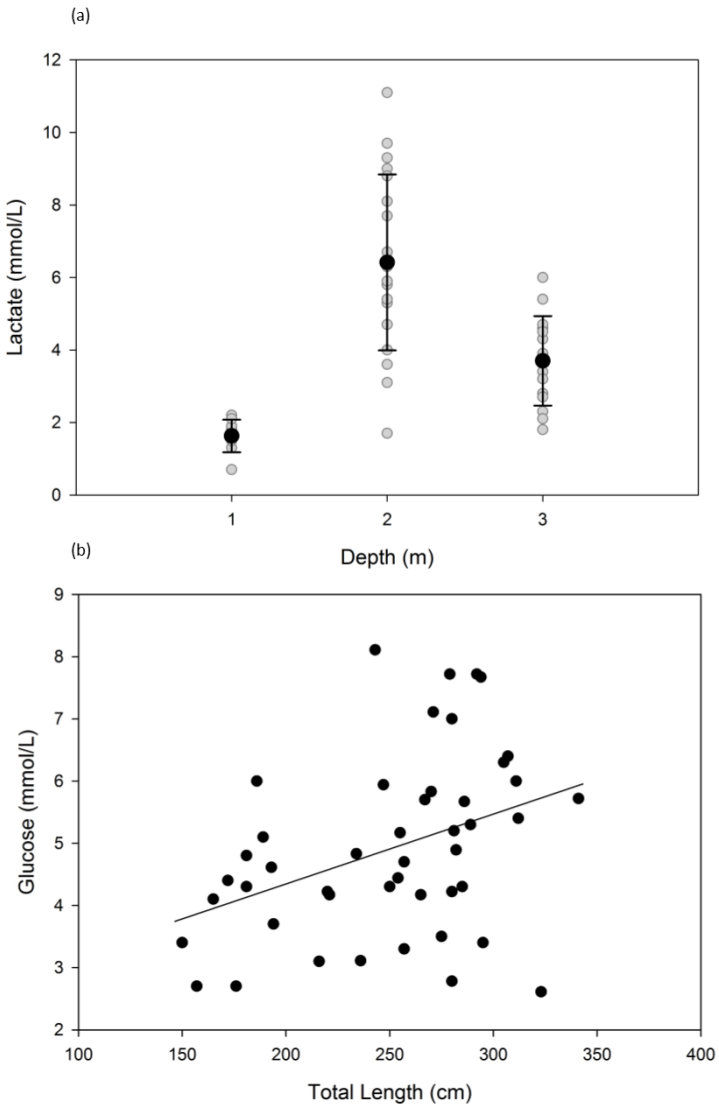

Figure 3.2 Stress metabolites for Greenland Sharks caught on longlines in Scott Inlet, Baffin Island. (a) Greenland Shark lactate values from three depth stratum (300-600, 600-700 and 700-900) where sharks captured between 300-600 m had significantly lower lactate concentrations than those captured in deeper water (One-way ANOVA: $F_{2, 43}$=40.52, p<0.001). Light grey dots are the original, untransformed data and the black dots are the mean ± one standard deviation. (b) Linear regression of Greenland Shark blood glucose with TL (F_{44}= 7.50, p<0.01, R^2= 0.15)

CHAPTER 4

General Conclusion

4.1 Summary

There exists a rich abundance of both abiotic and biotic natural resources within the Arctic, from minerals to oil, gas, fish and marine mammals. These reserves have the potential to help supplement dwindling southern supplies as global warming allows greater access to areas once logistically impossible to exploit. Developing industries also have the potential to bring much needed economic development to Arctic communities that currently face difficult socioeconomic conditions. Yet without research into the environmental impacts of developing the North, we run the risk of depleting these resources or damaging important natural processes. Most notably, increasing commercial pressure on marine fish can lead to ecosystem instability if scientific knowledge fails to provide instruction for proper management (Reist 1997, Christiansen et al. 2014).

The main objective of my thesis was to provide new information relevant to the developing Greenland Halibut (*Reinhardtius hippoglossoides*) fishery within the Canadian Arctic. This entailed increasing our knowledge on two important aspects of fisheries management: (i) stock identification through inshore/offshore connectivity of Greenland Halibut and (ii) fishery impact on discards through the capture induced stress of Greenland Sharks (*Somniosus microcephalus*) and Greenland Halibut. The first objective adheres to traditional management ideology that entails determining target species habitat use and movement patterns to prescribe sustainable harvesting practices. Fish stocks that cross management boundaries are at a higher risk of overexploitation when TACs (total allowable catch) fail to take into consideration the connectivity of harvested populations (Balton 1996). The second objective is grounded in ecosystem-based management that considers the effect fisheries can have on ecological processes and species that are not directly targeted. The physiological stress response of a species induced

by commercial capture can vary based on ontogeny as well as the environment in which it was captured. Identification of fishing practices or species life-stages that result in a larger stress response to commercial harvest can therefore lead to alterations within the fishery to reduce the risk of discard mortalities.

Contrary to my predictions, Chapter 2 determined that Greenland Halibut utilize both the inshore and offshore environment of Baffin Bay, opposite to evidence elsewhere that most Greenland Halibut within northern fjords are resident (Boje 2001, Boje et al. 2014). The majority of fish within this study moved offshore at the same time that ice began to develop within the inshore environment. However, there was also a small portion of fish that remained inshore throughout the year, suggesting that multiple distinct behavioral types exist for Greenland Halibut.

Chapter 3 determined that blood glucose concentration increased with length for both trawl caught Greenland Halibut and longline caught Greenland Sharks. Lactate increased linearly for Greenland Halibut with time spent held on the boat, yet the variability in the data (i.e. the residuals) also increased exponentially suggesting intraspecies variation in lactate levels resulting from capture. Greenland Sharks also displayed an increase in lactate levels as capture depth increased, indicating that greater physiological perturbations result from pulling sharks up from greater depths.

4.2 Implications and Future Directions

Scott Inlet and Sam Ford Fjord are deep-water fjords located on the northern face of Baffin Island, Canada. A traditional hunting ground for Inuit, Scott Inlet is host to many marine and terrestrial animals such as seals (ringed (*Phoca hispida*) and harp (*Pagophilus groenlandicus*)), narwhale (*Monodon monoceros*), polar bears (*Ursus maritimus*), and a diverse bird community. The nearby community of Clyde River continues to use this area for subsistence hunting in order to supplement their diet with these nutrient rich animals. The development of a

fishery based out of Clyde River, targeting Greenland Halibut in Scott Inlet and Sam Ford Fjord has the potential to provide needed economic input to this community, which adheres to their traditions of hunting and trapping. As in Pangnirtung, another Baffin Island Inuit community with a successful Greenland Halibut fishery, if artisanal ice fishing for Greenland Halibut proves to be profitable in Clyde River, it is possible that money will become available to develop infrastructure needed for fishing vessels. With a dock and ports in Clyde River, the community will then also be able to take part in summer and offshore harvesting.

Based on movement data from acoustically tagged Greenland Halibut in Scott Inlet and Sam Ford Fjord, multiple scenarios may result from the development of a Clyde River fishery. First, if any summer harvesting of Greenland Halibut takes place within Scott Inlet, the weight of this harvest should be subtracted from the TAC of the offshore fishery (in NAFO division 0A). Greenland Halibut use the inshore environment of Scott Inlet during the ice-free months, and thus the offshore and inshore fishery will target the same fish as they migrate to and from both environments. Currently, the offshore fishery has a set TAC of 6400 tones, notably smaller than many other fisheries, yet 100 tones has been designated to areas within the Nunavut Settlement Area (NSA) to encourage development (DFO 2013). Should a Scott Inlet fishery take hold, these numbers would have to be re-assessed to allocate more resources to the inshore fishery. This data can greatly benefit from multiple years of tracking, as opposed to the one year presented in this thesis. Important questions still remain such as: do the same fish continue to return each year? Upon returning, do these fish perform similar small-scale movements throughout the system consistently each year? Is it possible for an individual to switch from transitory to resident? Answering some of these questions can give greater insight into both Greenland Halibut ecology and management.

The second scenario, and possibly the more pressing issue, considers the development of a fishery in Clyde River that targets Greenland Halibut in the winter months, through the ice. Considering Clyde River currently lacks the infrastructure to support fishing vessels, this would

likely be the first stage of developing a fishery in the area. Acoustic tracking identified a small group of tagged fish that were resident within Scott Inlet that would likely be the target of a through-ice fishery. Given they are potentially separate from the offshore environment, a winter fishery can therefore be hypothetically managed separately from the offshore stock. However, if the residents are truly a sink population, meaning that the fish do not migrate to spawn, and what little spawning occurs in the fjords is not enough to support the population, then the winter fishery will be highly dependent on the productivity of the spawning stock (or source population) (Milner-Gulland 2001, Boje 2001, Boje et al. 2014). A multi-year approach to the resident population would also better determine if these fish are truly resident. This also includes tagging fish captured during the winter in Scott Inlet, which would insure that the majority of fish present at this time are the same as the resident population.

Fisheries for other groundfish such as Atlantic and Pacific Halibut, have existed in Canada for much longer compared to the developing Greenland Halibut fishery. One of the greatest defining features that separates management practices between these fisheries is the lack of knowledge on Greenland Halibut that hinders efforts to model population dynamics. Management practices such as TACs are established for Greenland Halibut fisheries through assessing the catch of commercial vessels, whereas this method is used in conjunction with population modeling for other groundfish species that allows for future population projections. Secondly, due to the high vulnerability of groundfish to overexploitation, policy was established to prohibit harvesting of Atlantic Halibut below the size of 81 cm (DFO 2015). Similar policies exist for Greenland Halibut that entails the fishery will be closed when catch of undersized fish exceeds 15% of the commercial harvest, yet this is not heavily enforced (DFO 2013). Most other aspects of the fishery are similar, as they all require at-sea coverage by observers and limitations to gear types and sizes (DFO 2013, 2015).

The physiological consequences of capture in both Greenland Shark and Greenland Halibut can have specific implications for developing a Greenland Halibut fishery within Scott

Inlet and Sam Ford Fjord. Namely, this area has been identified as a potential nursery for Greenland Sharks given the high abundance of juveniles captured within the fjords (Hussey et al. 2015). Although smaller sharks do not express greater physiological disturbance as a consequence of capture, fishing at the maximum depths of the system (>800 m) can result in increased lactate concentrations that may be deleterious upon release. As it is likely that a Scott Inlet fishery will capture juveniles and potentially pregnant female Greenland Sharks, fishing at great depths within Scott Inlet should possibly be avoided to reduce the impact fishing has the shark population. Small Greenland Halibut did not show any greater physiological change compared to larger fish that may demonstrate reduced fitness of undersized individuals upon release. This suggests that, from a fisheries perspective, if it is possible to separate juvenile Greenland Halibut quickly from the catch, releasing them is a potentially viable option for conservation. However, more data is still needed to determine the true consequences of fisheries capture on discards post-release, which can ultimately be supplied by acoustic telemetry.

This thesis presents two modern techniques that are currently available to assess fisheries sustainability. Although acoustic telemetry and physiology were presented in separate chapters to answer two different questions pertaining to fisheries development, these two techniques can be used in tandem for future studies to provide a robust and detailed exploration of behaviour and survival. As briefly mentioned in Chapter 3, the Greenland Sharks within that study were tagged with acoustic transmitters similar to those described in Chapter 2 for Greenland Halibut. From this, it was determined that the shark expressing the highest recorded lactate value of 11 mmol/L likely died as it was never detected on any of the acoustic gates utilized to track Greenland Halibut in Chapter 2. No serious conclusions can be drawn from this observation, yet it demonstrates the effectiveness of combining acoustic telemetry and physiology for future studies.

Many tracking studies wish to optimize the survival of their tagged fish, as this provides the data needed for determining movement and migration patterns. Drawing blood prior to tag insertion, then using point-of-care devises as those described in Chapter 3 can give immediate

results on the fish's lactate and glucose levels and advise if tagging should be performed. Yet, it is arguably preferable to tag fish expressing a wide range of physiological values, as this information can provide valuable insight into the vulnerability of different behavioral types (Cooke et al. 2008). The wide variation in lactate values for Greenland Halibut after three hours of being held in a tank on the boat suggest that some individuals either recovered faster than others, or failed to mount a significant stress response. It is interesting to consider that the variability in stress response might also be associated with the variability in behaviour and habitat use described in Chapter 2.

Investigations into the association of migration and physiology at the time of tagging are just beginning to develop (Cooke et al. 2008). An investigation by Cooke et al. (2006) determined that a high lactate concentration in Sockeye Salmon (*Oncorhynchus nerka*) at the time of tagging was associated with failure to migrate into spawning streams. Although stress levels could predict migration success, they weren't associated with later migration timing upstream (Cook et al. 2014). These studies focus on migration success and not variation in natural behaviour, yet this may establish the foundations for future work to investigate how variation in migration behaviour and habitat use in fish can increase their risk for capture related stress in fisheries (Cooke et al. 2012).

Fisheries within Canada are managed by the Department of Fisheries and Oceans (occasionally in cooperation with local management groups such as the Nunavut Wildlife Management Board) which is guided by legislature such as the Fisheries Act (DFO: Mission, Vision and Values). It is through the Fisheries Act that regulations are implemented for the sustainable conservation of Canadian fisheries and the ecosystems which support them (Fisheries Act: R.S.C., 1985, c. F-14; last amended 2015). However concerns have been raised recently that amendments to the act reduce its focus on ecosystems (fish habitat) to be centered more prominently upon targeted commercial fish. Although further work is needed, results from this thesis suggest that there is potential to reduce the impact of Greenland Halibut fisheries on

Greenland Sharks if capture depths are reduced, indicating that continuing research in ecosystem management is a preferable direction over simple target-species based management.

In conclusion, this thesis presents novel information on Greenland Halibut ecology, as well as Greenland Halibut and Greenland Shark physiology. Presented above are all the management benefits afforded the community of Clyde River for fisheries development in Scott Inlet and Sam Ford Fjord resulting from this research, yet it is also highly applicable to the entire fishery across the North. There likely exists a single population of Greenland Halibut within the North Atlantic Ocean (Vis et al. 1997, Roy et al. 2014), suggesting that the stock harvested by each fishery is highly interconnected with the next. Management therefore requires a high degree of cooperation between states to develop sustainable practices. In this respect, this research contributes to the relative lack of knowledge currently available for Arctic fisheries in order to advise and inform these practices.

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VITA AUCTORIS

NAME:	Amanda Noël Barkley
PLACE OF BIRTH:	Windsor, ON
YEAR OF BIRTH:	1990
EDUCATION:	Sandwich West Secondary School, Windsor, ON, 2008
	University of Windsor, BA &.Sc., Windsor, ON, 2013